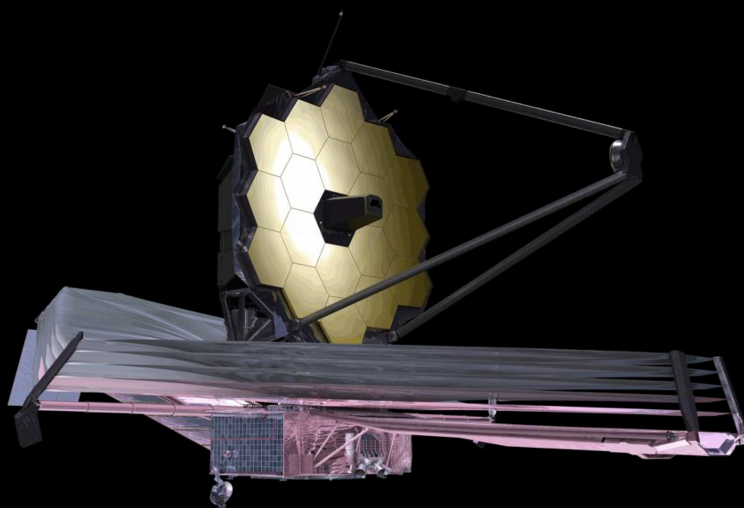
James Webb Space Telescope (JWST)



The First Light Machine

What is FIRST LIGHT?

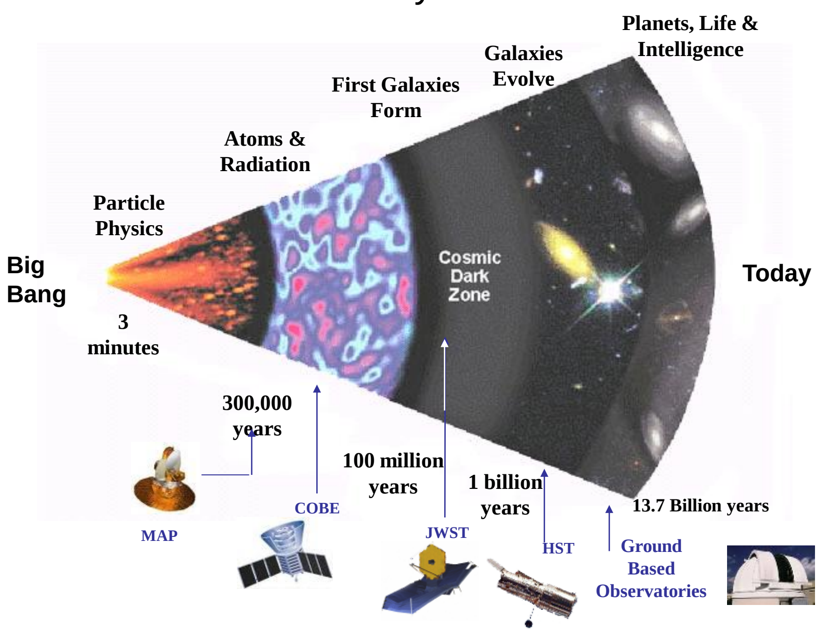
End of the dark ages: first light and reionization

What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did re-ionization of the inter-galactic medium occur?
What caused the re-ionization?

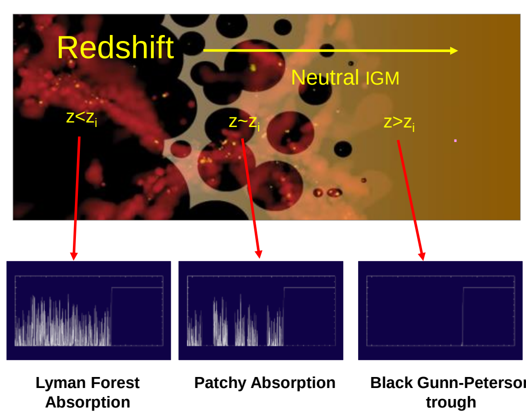
… to identify the first luminous sources to form and to determine the ionization history of the early universe.

Hubble Ultra Deep Field

A Brief History of Time



First Light: Observing Reionization Edge

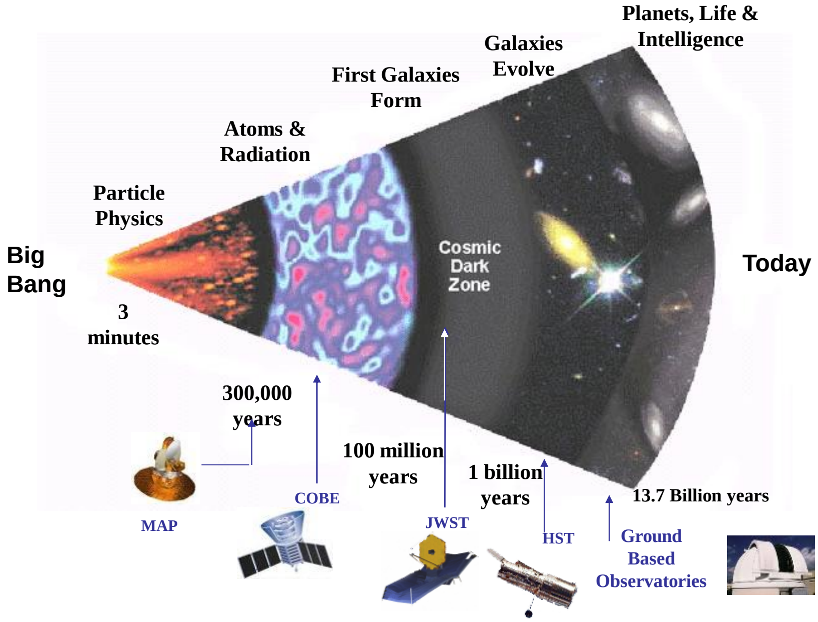


Reionization started at about 600 M yrs after Big Bang. At 780 M yrs after BB the Universe was up to 50% Neutral. But, by 1 B years after BB is was as we see it today. 787 M yr Galaxy confirmed by Neutral Hydrogen method.

Neutral 'fog' was dissolved by very bright 1st Generation Stars (5000X younger & ~100X more massive than our sun).

SPACE.com, 12 October 2011

A Brief History of Time



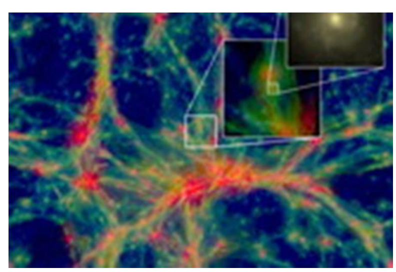
Cosmic Web

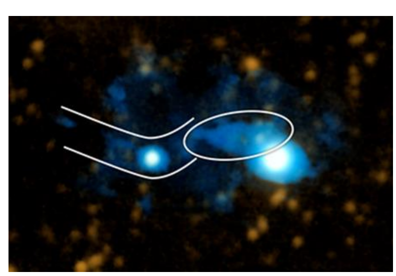
Ripples in the early universe formed long filaments of hydrogen gas surrounded by 'dark matter'.

Galaxies form at crossing points.

Most of universe's matter is in these filaments and dark matter.

This one is 10B light years away.



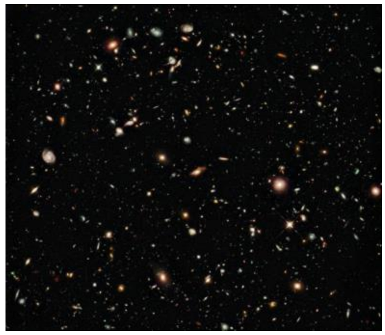


A filament of the universe's "cosmic web" is highlighted with parallel curved lines in this image, while a protogalaxy is outlined with an ellipse. The brightest spot (on the lower right side of the ellipse) is the quasar UM287. The other bright spot is a second quasar in the system. The image combines a visible light image with data from the Cosmic Web Imager.

CREDIT: Chris Martin/PCWI/Caltech

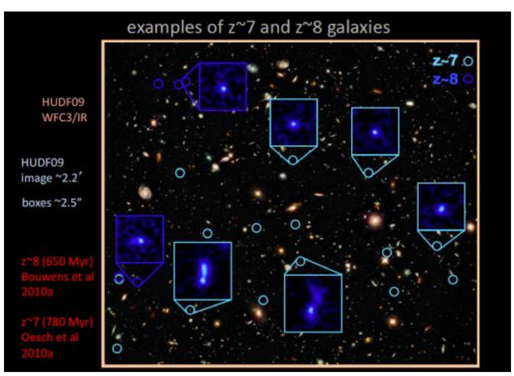
Charles Choi, Space.com, 5 Aug 2015.

Hubble Ultra Deep Field – Near Infrared



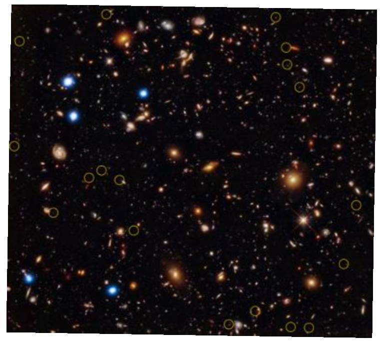
Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

Hubble Ultra Deep Field – Near Infrared



47 Galaxies have been observed at 600 to 650 Myrs after BB.

Hubble Ultra Deep Field – Near Infrared
Chandra Deep Field South



CREDIT: X-ray: NASA/CXC/U.Hawaii/E.Treister et al; Optical: NASA/STScl/S.Beckwith et al

Keith Cooper, Astronomy Now, 15 June 2011
Taylor Redd, SPACE.com, 15 June 2011

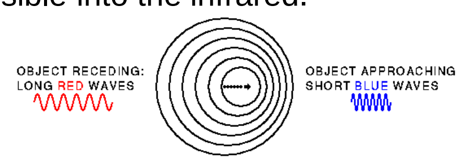
What came first – Galaxies or Black Holes?

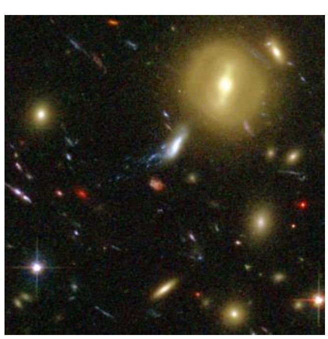
Each of these ancient 700 M yrs after BB galaxies has a black hole.

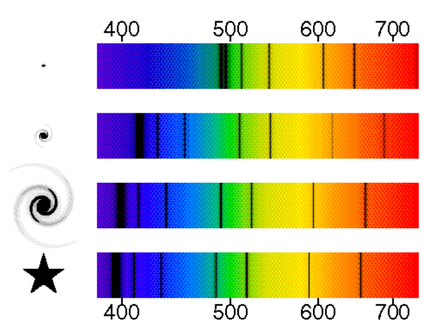
Only the most energetic x-rays are detected, indicating that the black-holes are inside very young galaxies with lots of gas.

Redshift

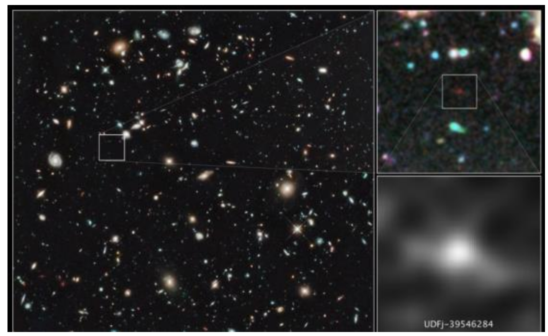
The further away an object is, the more its light is redshifted from the visible into the infrared.



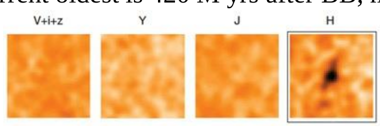




Hubble Ultra Deep Field – Near Infrared



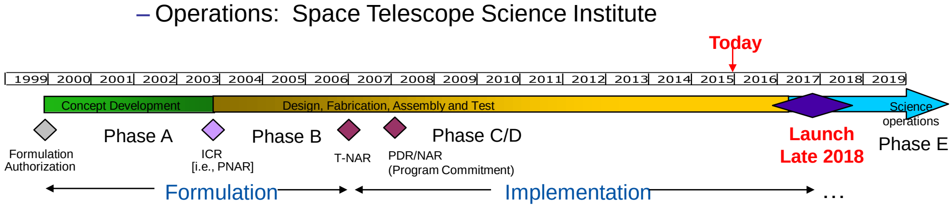
At 480 M yrs after big bang (z ~ 10) this one of oldest observed galaxy. Discovered using drop-out technique.
(current oldest is 420 M yrs after BB, maybe only 200 M yrs)



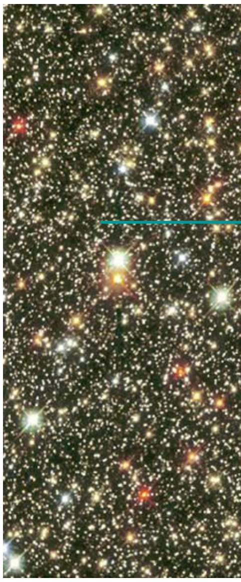
Left image is visible light, and the next three in near-infrared filters. The galaxy suddenly pop up in the H filter, at a wavelength of 1.6 microns (a little over twice the wavelength the eye can detect). (Discover, Bad Astronomy, 26 Jan 2011)

JWST Summary

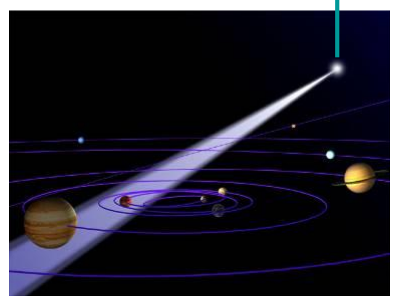
- **Mission Objective**
  - Study origin & evolution of galaxies, stars & planetary systems
  - Optimized for near infrared wavelength (0.6 –28 μm)
  - 5 year Mission Life (10 year Goal)
- **Organization**
  - Mission Lead: Goddard Space Flight Center
  - International collaboration with ESA & CSA
  - Prime Contractor: Northrop Grumman Space Technology
  - Instruments:
    - Near Infrared Camera (NIRCam) – Univ. of Arizona
    - Near Infrared Spectrometer (NIRSpec) – ESA
    - Mid-Infrared Instrument (MIRI) – JPL/ESA
    - Fine Guidance Sensor (FGS) – CSA
  - Operations: Space Telescope Science Institute



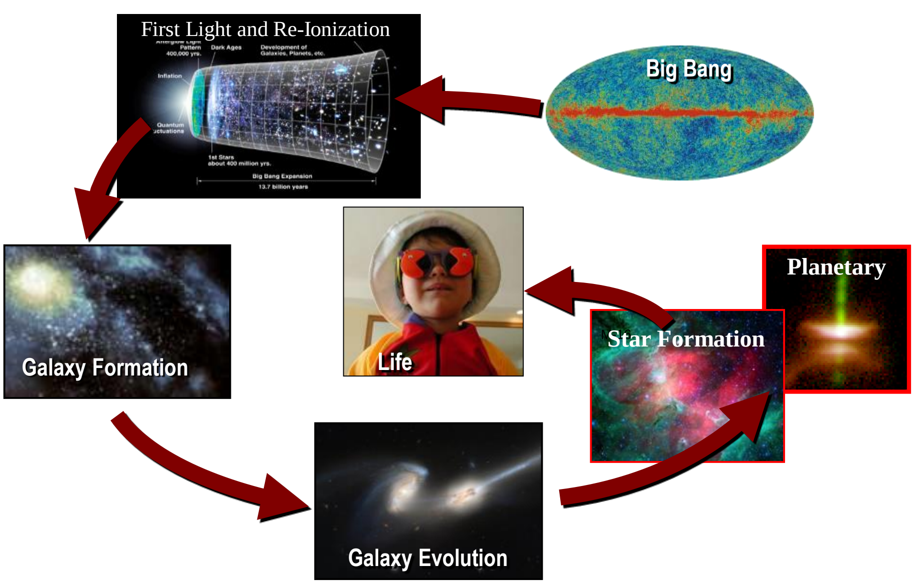
Origins Theme's Fundamental Questions



- How Did We Get Here?
- Where Are We Going?
- Are We Alone?



JWST Science Themes



Three Key Facts

There are 3 key facts about JWST that enables it to perform is Science Mission:

It is a Space Telescope

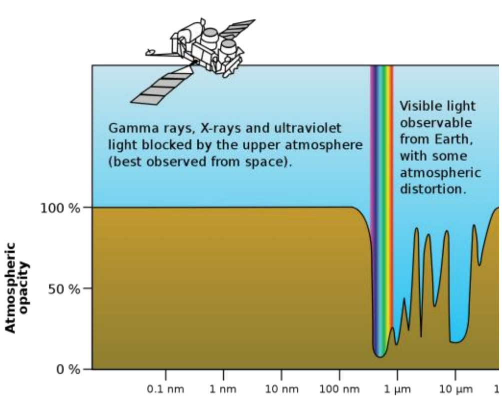
It is an Infrared Telescope

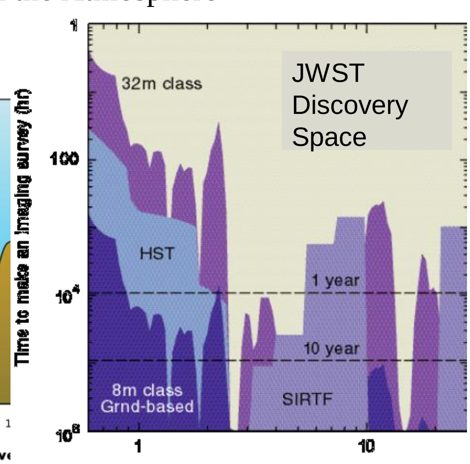
It has a Large Aperture

Why go to Space

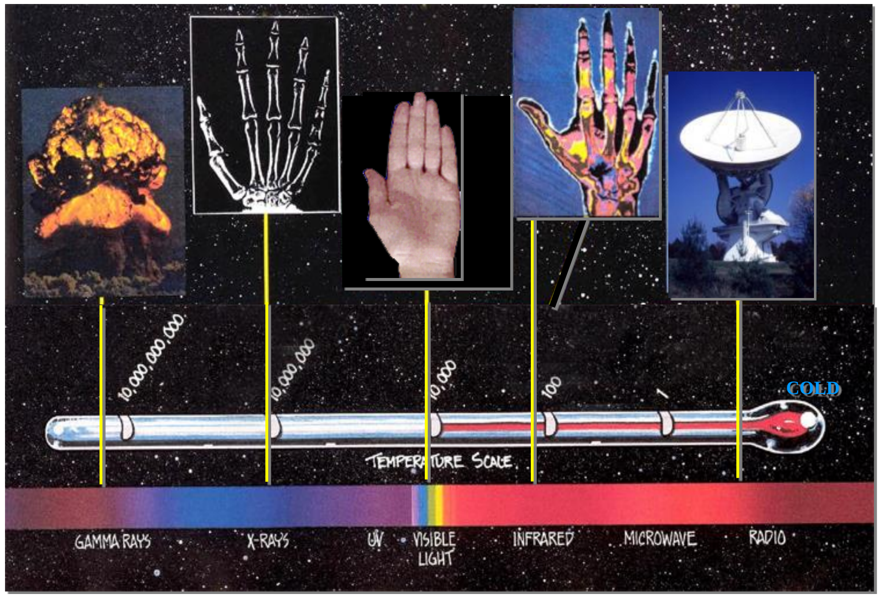
Atmospheric Transmission drives the need to go to space.

Infrared (mid and far/sub-mm) Telescopes (also uv, x-ray, and gamma-ray) cannot see through the Atmosphere





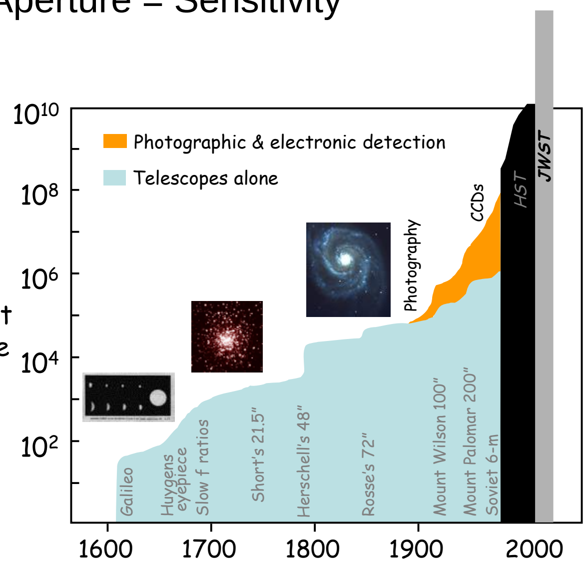
Infrared Light



Why Infrared ?

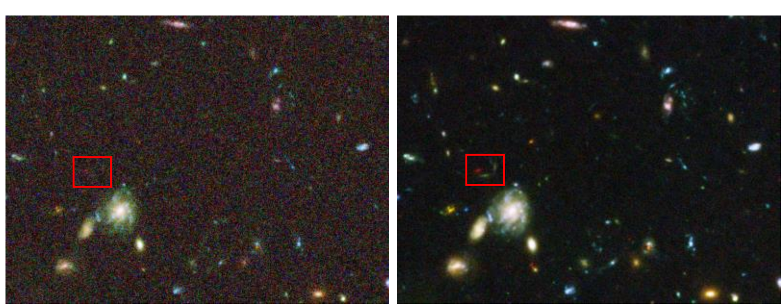
Why do we need Large Apertures?

Aperture = Sensitivity

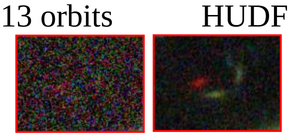


Adapted from *Cosmic Discovery*, M. Harwit

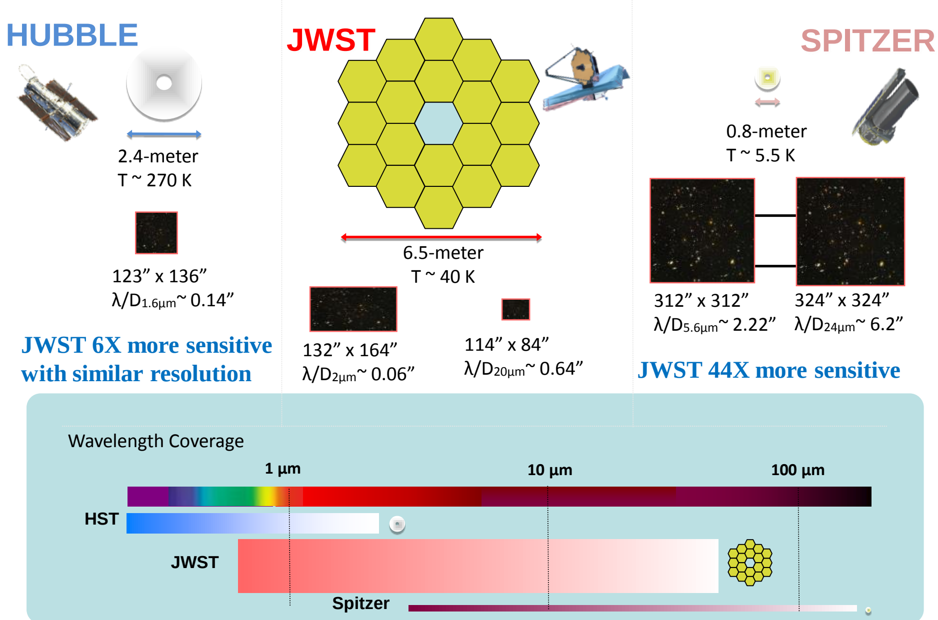
Sensitivity Matters



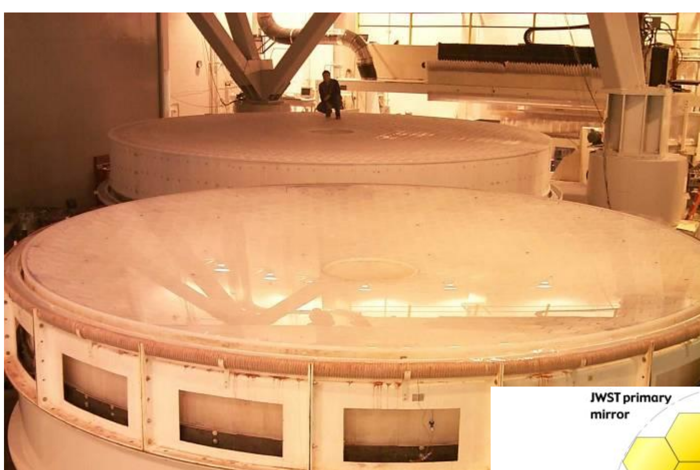
GOODS CDFS – 13 orbits HUDF – 400 orbits

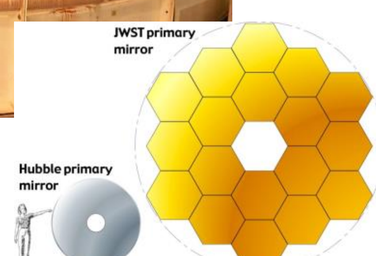


JWST will be more Sensitive than Hubble or Spitzer



How big is JWST?

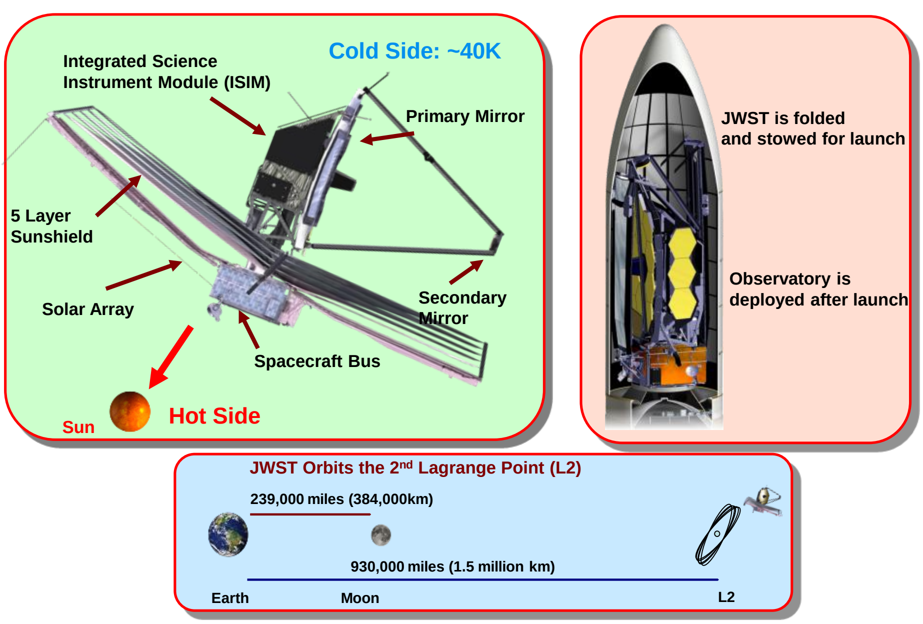




Full Scale JWST Mockup

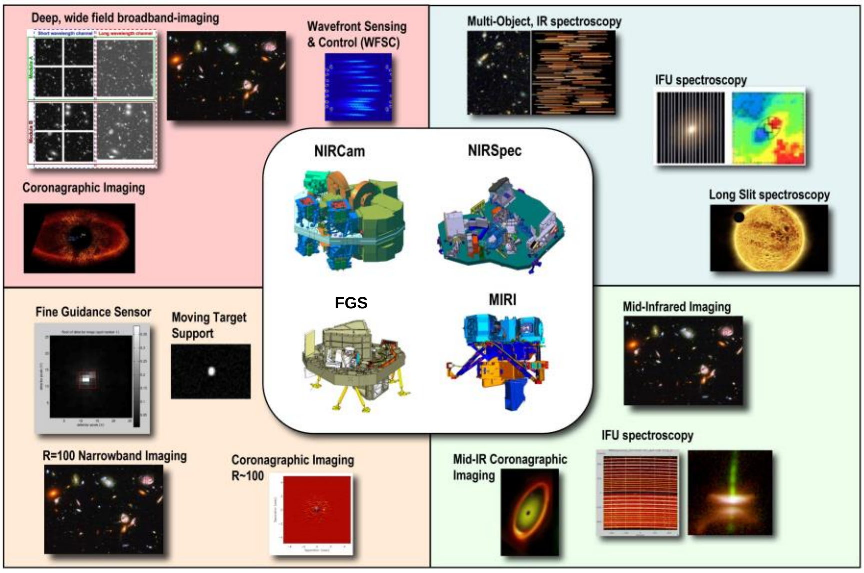
21st National Space Symposium, Colorado Springs, The Space Foundation

How JWST Works



JWST Science Instruments

enable imagery and spectroscopy over the 0.6 – 29 micron spectrum



JWST Requirements

Optical Telescope Element

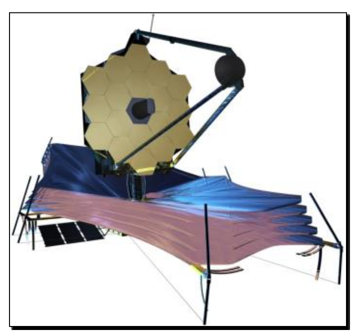
- 25 sq meter Collecting Area
- 2 micrometer Diffraction Limit
- < 50K (~35K) Operating Temp

Primary Mirror

- 6.6 meter diameter (tip to tip)
- < 25 kg/m^2 Areal Density
- < \$6 M/m^2 Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

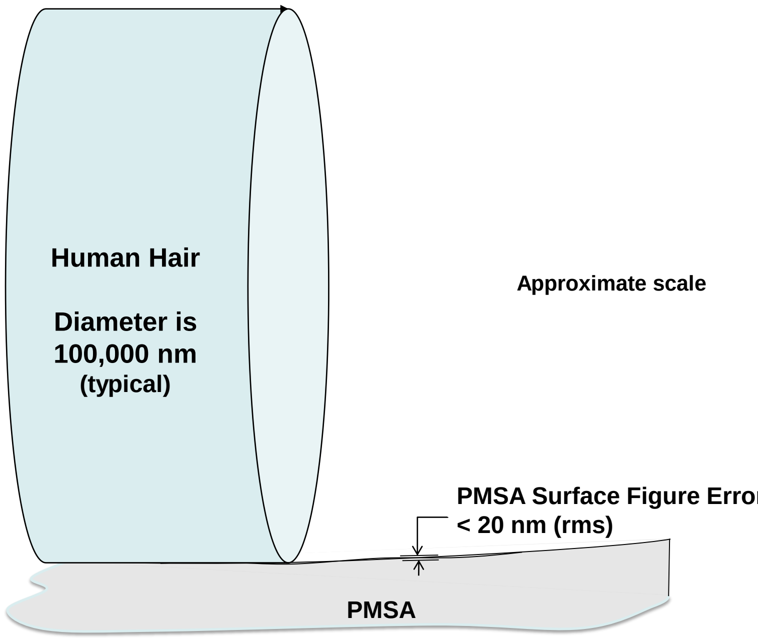
Segments

- 1.315 meter Flat to Flat Diameter
- < 20 nm rms Surface Figure Error

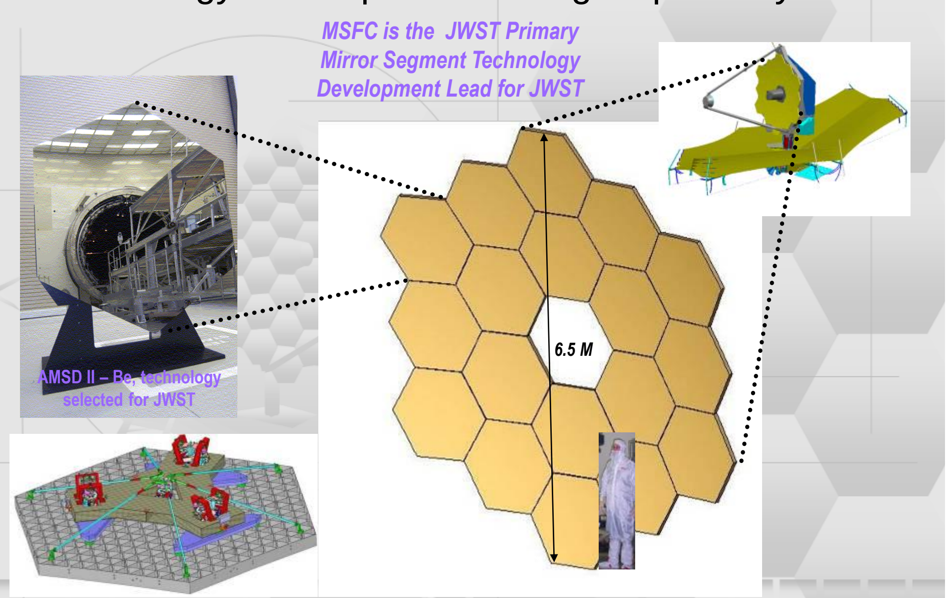


Low (0-5 cycles/aper)	4 nm rms
CSF (5-35 cycles/aper)	18 nm rms
Mid (35-65K cycles/aper)	7 nm rms
Micro-roughness	<4 nm rms

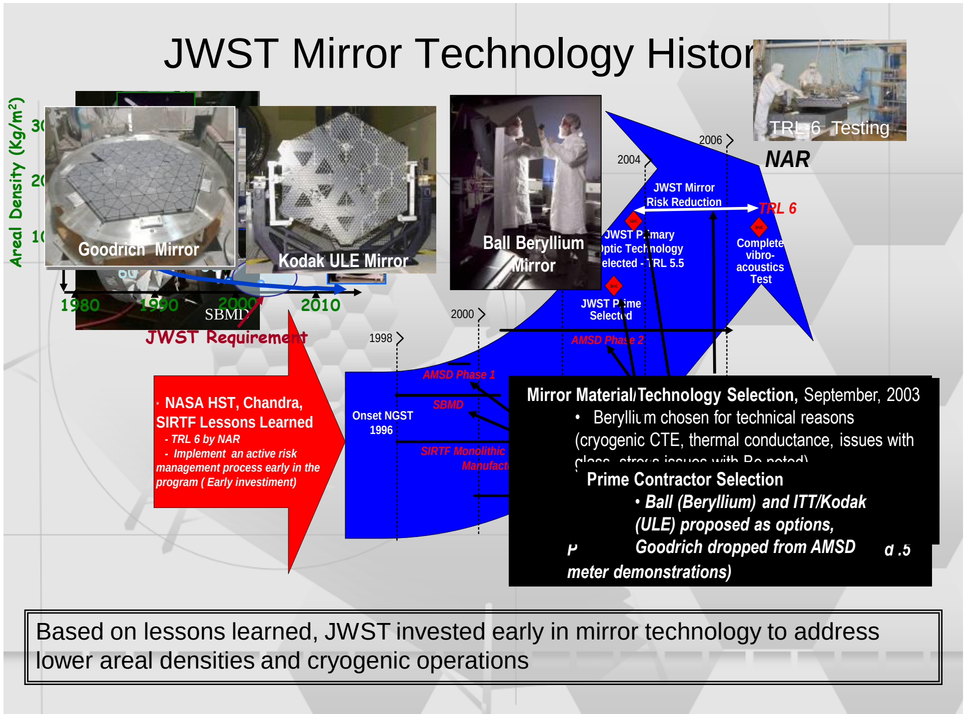
Fun Fact – Mirror Surface Tolerance



Technology Development of Large Optical Systems



The 18 Primary Mirror segments



Advantages of Beryllium

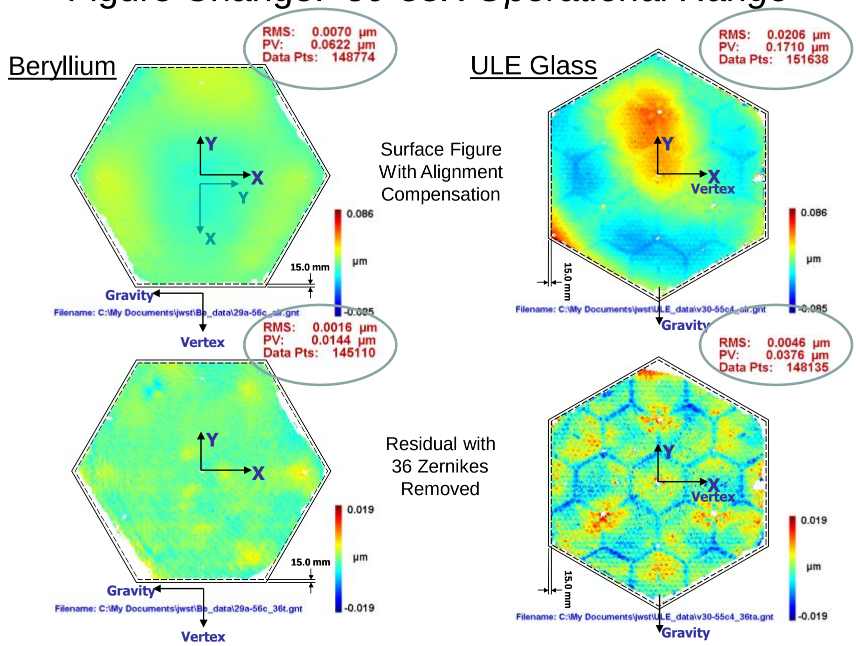
Very High Specific Stiffness – Modulus/Mass Ratio

Saves Mass – Saves Money

High Conductivity & Below 100K, CTE is virtually zero.

Thermal Stability

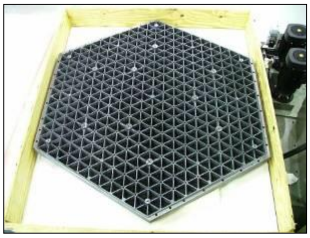
Figure Change: *30-55K Operational Range*



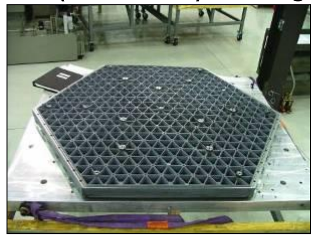
Brush Wellman

Axsys Technologies

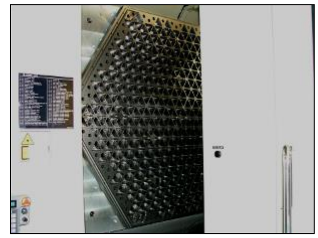
Batch #1 (Pathfinder) PM Segments



PMSA #1 (EDU-A / A1)



PMSA #2 (3 / B1)

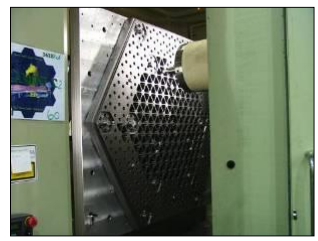


PMSA #3 (4 / C1)

Batch #2 PM Segments

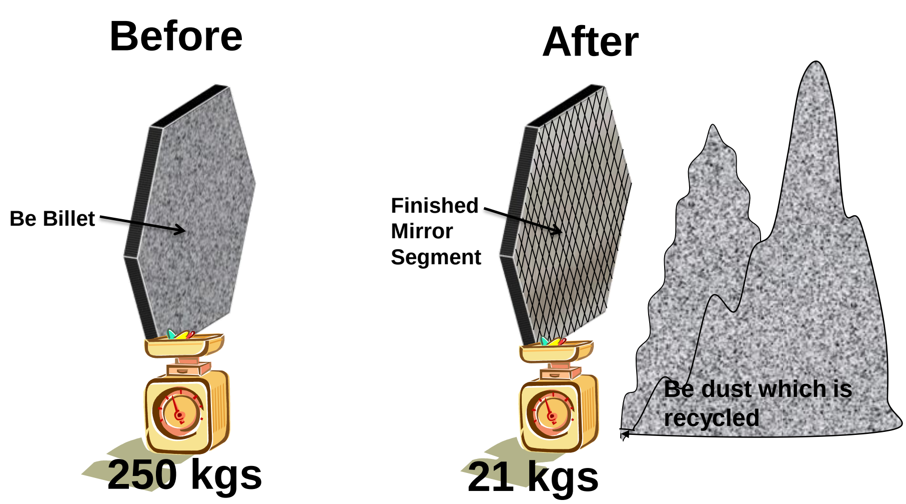
PMSA #4 (5 / A2)

PMSA #5 (6 / B2)



PMSA #6 (7 / C2)

Fun Facts – Mirror Manufacturing



Over <u>90%</u> of material is removed to make each mirror segment – want a little mirror with your Be dust?

Mirror Processing at Tinsley

Optical Testing Challenge

JWST

- In-Process Optical Testing
- Requirement Compliance Certification Verification & Validation

is probably the most difficult metrology job of our generation

But, the challenge has been met:

- by the hard work of dozens of optical metrologists,
- the development and qualification of multiple custom test setups, and
- several new inventions, including 4D PhaseCam and Leica ADM.

Tinsley In-Process Metrology Tools

Metrology tools provide feedback at every manufacturing stage:

Rough Grinding	CMM
Fine Grinding/Rough Polishing	Scanning Shack-Hartmann
Final Polishing/Figuring/CNF	Interferometry

PMSA Interferometer Test Stations included:

- 2 Center of Curvature CGH Optical Test Stations (OTS1 and OTS2)
- Auto-Collimation Test Station

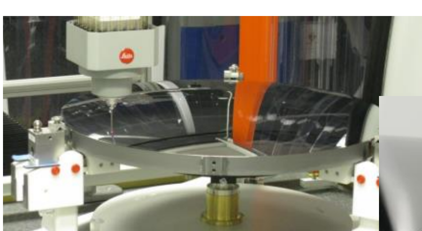
Data was validated by comparing overlap between tools

Independent cross check tests were performed at Tinsley and between Tinsley, Ball and XRCF.

Leitz CMM

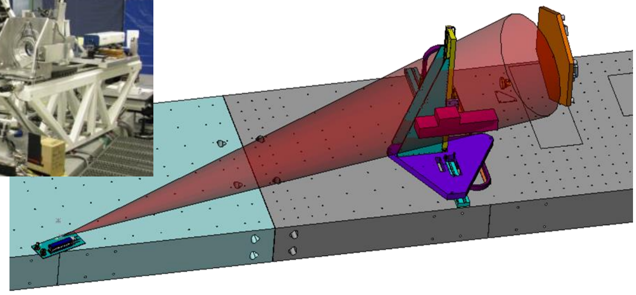
Provided Low-Order Figure and Radius of Curvature Control

Over course of program, software and process improvements dramatically reduced cycle time and increased data density



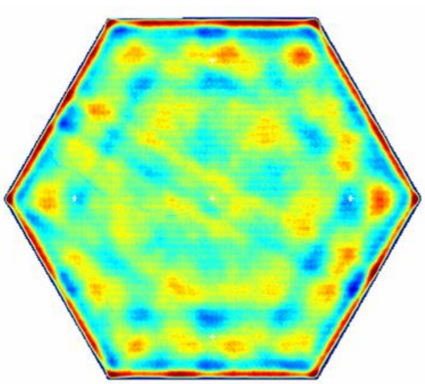
Wavefront Sciences Scanning Shack-Hartmann

- SSHS provided bridge-data between grind and polish, used until PMSA surface was within capture range of interferometry
- SSHS provide mid-spatial frequency control: 222 mm to 2 mm
  - Large dynamic range (0 – 4.6 mr surface slope)
- When not used, convergence rate was degraded.

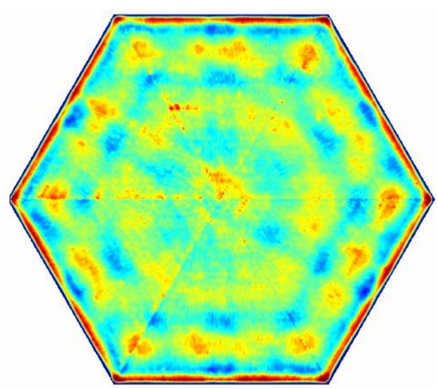



Comparison to CMM (222 - 2 mm spatial periods) 8/1/2006 data

Smooth grind



SSHS
4.7 µm PV, 0.64 µm RMS



CMM
4.8 µm PV, 0.65 µm RMS

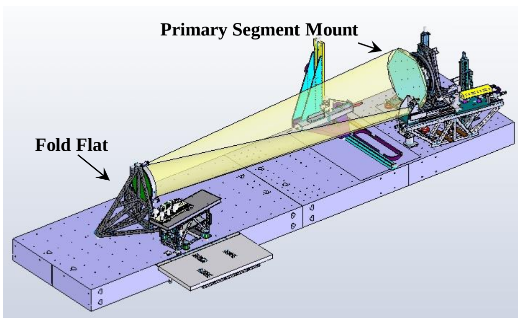
Point-to-Point Subtraction: SSHS - CMM = 0.27 µm RMS

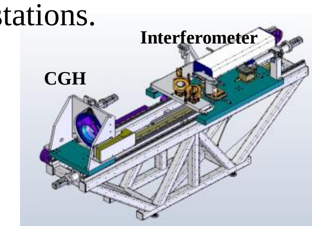
Full Aperture Optical Test Station (OTS)

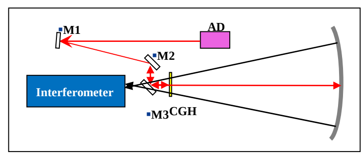
Center of Curvature Null Test (Prescription, Radius & Figure)

- PMSAs measured in 6 rotational positions to back-out gravity
- ADM – measures spacing between CGH and segment
- CGH – generates aberrated wavefront
- Quad cells – mounted to segments measure displacement of spots projected through CGH to determine parent vertex location

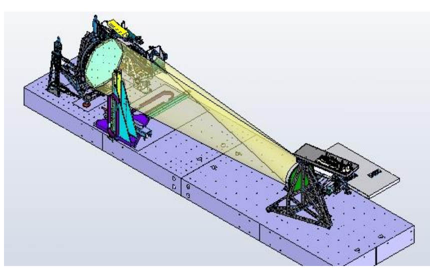
Results are cross-checked between 2 test stations.





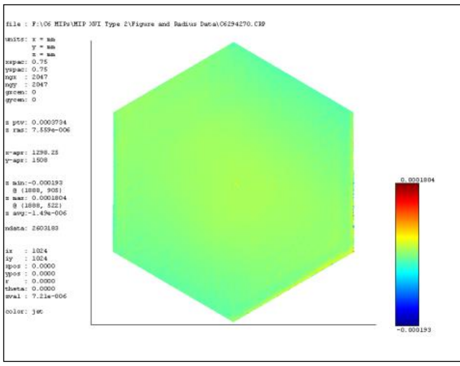


Full Aperture Optical Test Station (OTS)

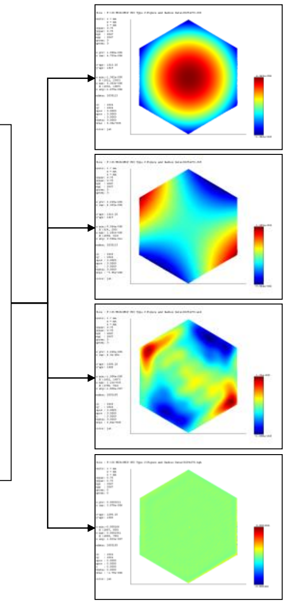


Test Reproducibility

(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270



Total Surface Delta:
PV: 373 nm
RMS: 7.6 nm



Power (Radius Delta: 0.02 mm)

Astigmatism: 4.4 nm RMS

Mid Frequency: 4.3 nm RMS

High Frequency: 3.9 nm RMS

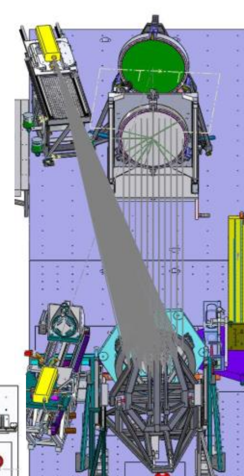
Auto-Collimation Test

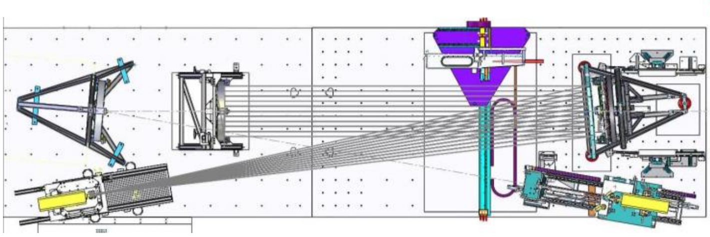
Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:

- Radius of Curvature
- Conic Constant
- Off-Axis Distance
- Clocking

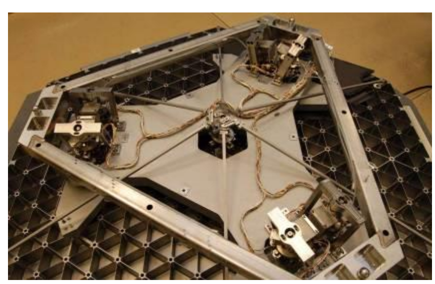
Note: is not a full-aperture figure verification test

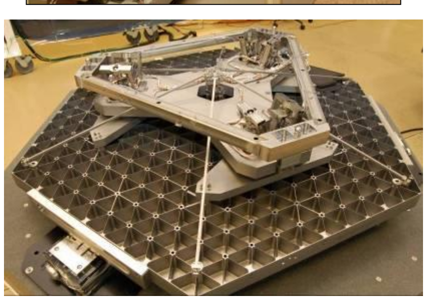




Tinsley Laboratory – Final Shipment

Primary Mirror Segment Assembly at BATC



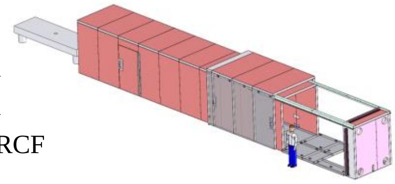


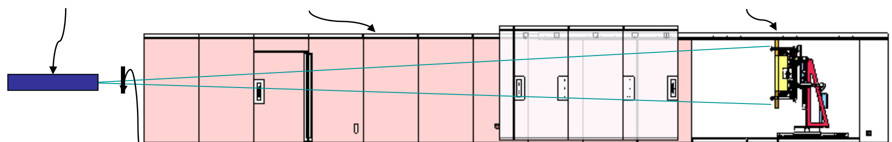
Ball Optical Test Station (BOTS)

Tinsley ambient metrology results are 'cross-checked' at BATC

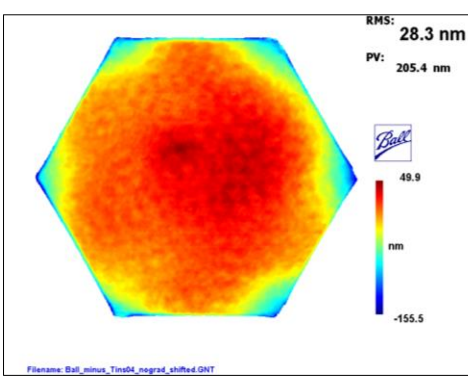
BOTS measurements:

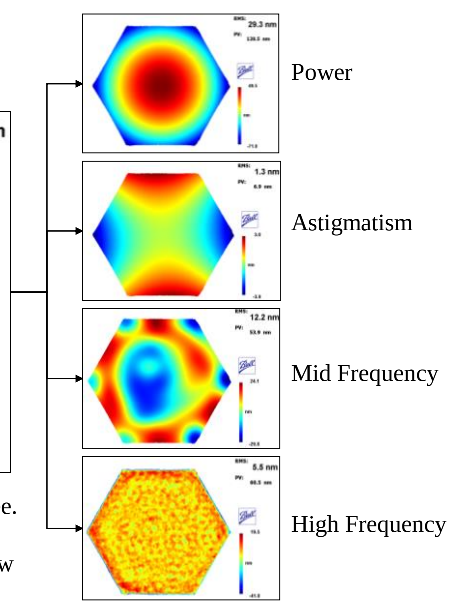
- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation





BOTS to Tinsley Initial Comparison

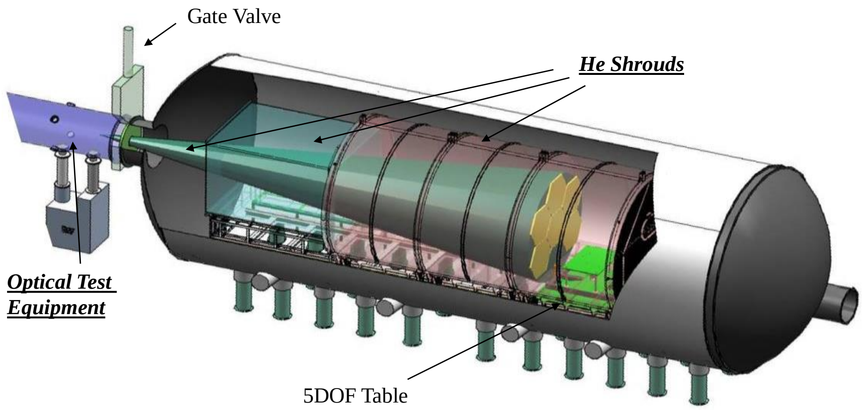




Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.

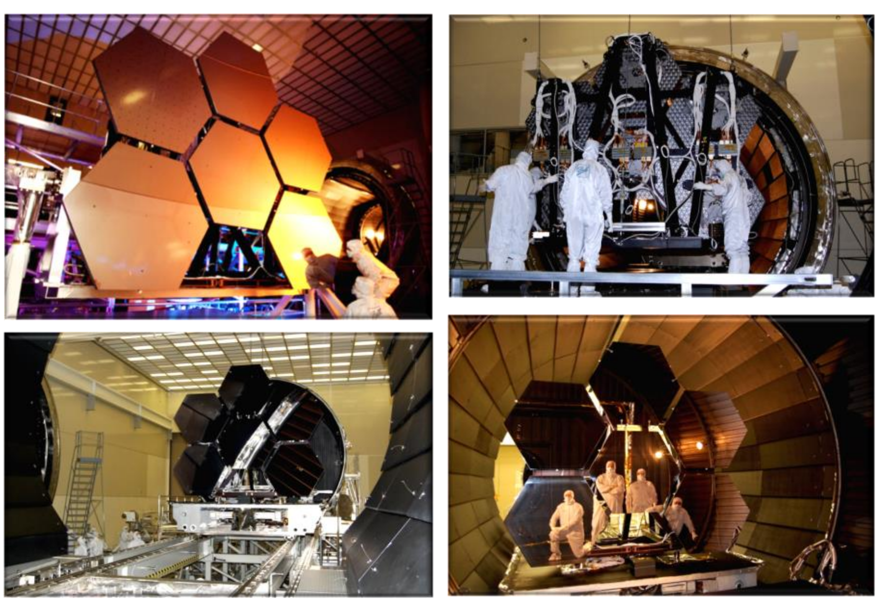
PMSA Flight Mirror Testing at MSFC XRCF

Cryogenic Performance Specifications are Certified at XRCF

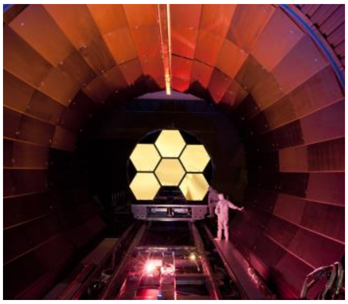


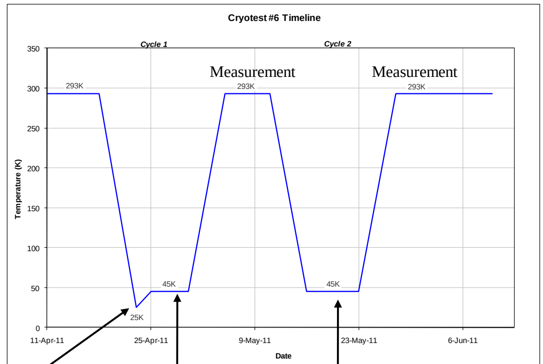
Cryo-Vacuum Chamber is 7 m dia x 23 m long

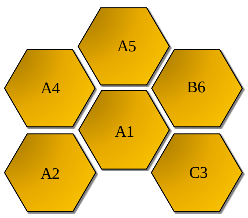
Primary Mirror Cryogenic Tests



XRCF Cryo Test





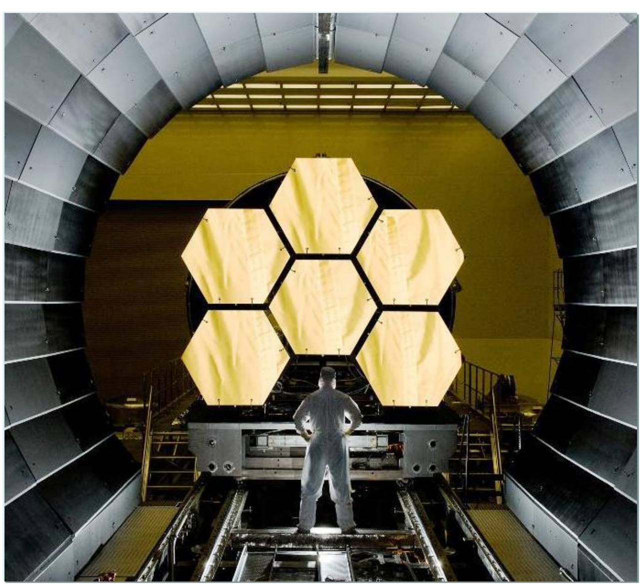


- Survival Temperature

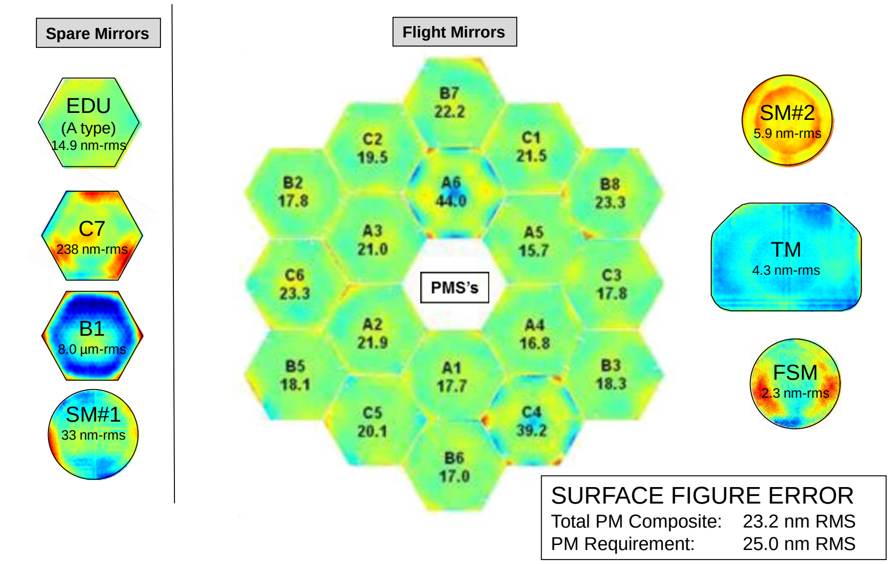
- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

Flight Mirrors in XRCF

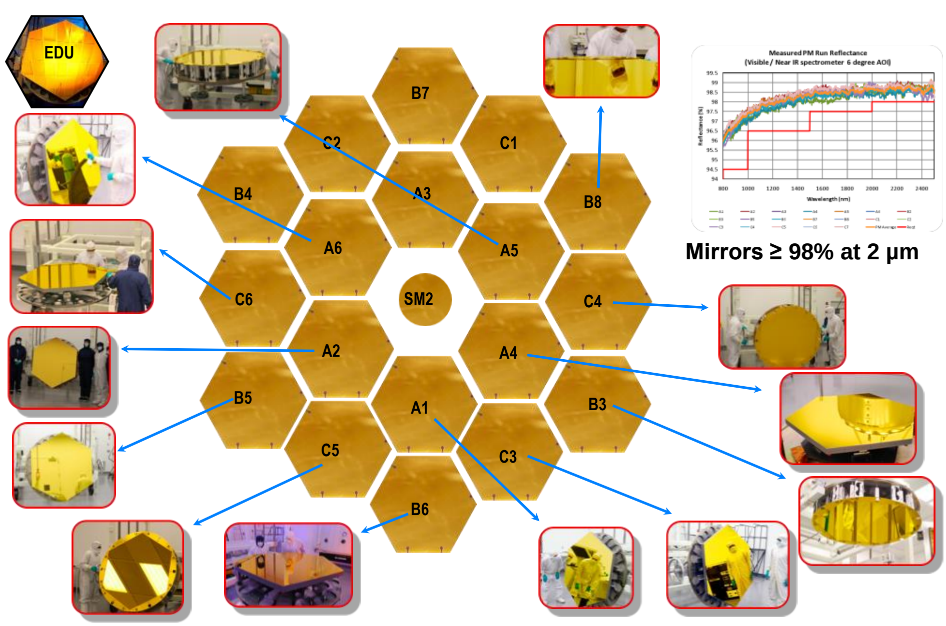


Mirror Fabrication Status
ALL DONE & DELIVERED



James Webb Space Telescope: large deployable cryogenic telescope in space. Lightsey, Atkinson, Clampin and Feinberg, Optical Engineering 51(1), 011003 (2012)

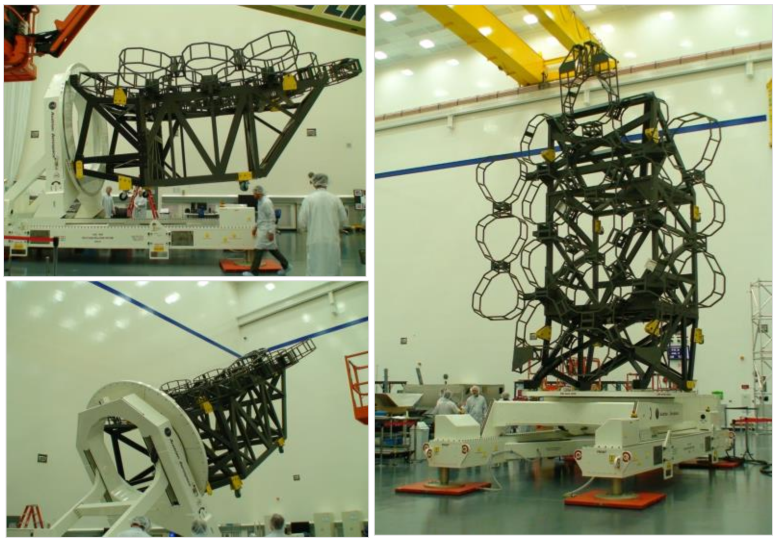
Gold Coated Mirror Assemblies



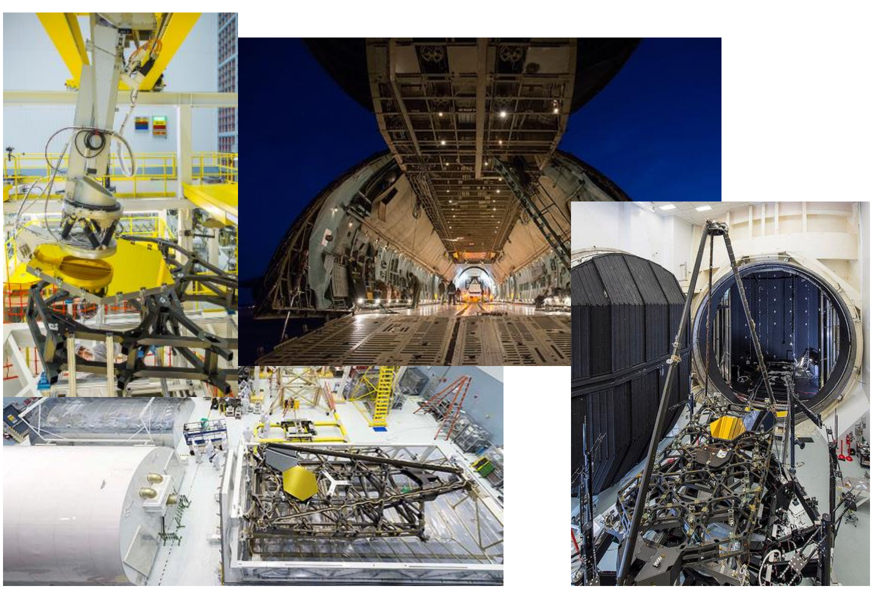
Primary Mirror Backplane

Pathfinder backplane (central section) is complete for test procedure verification at JSC

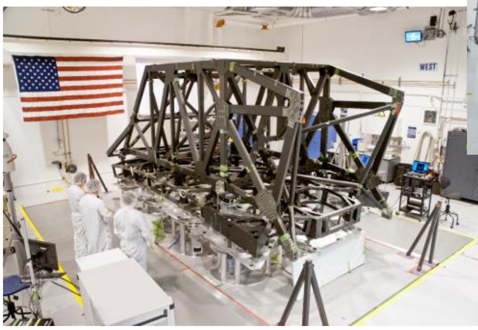
Flight Backplane under construction



Pathfinder Testing



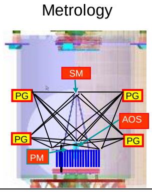
Flight Backplane Testing



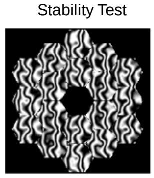
Observatory level testing occurs at JSC Chamber A

Verification Test Activities in JSC Chamber-A

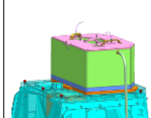
Cryo Position Metrology



Primary Mirror Stability Test

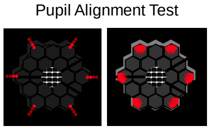


Focus Sweep Test (inward facing sources)

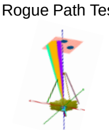


Crosscheck Tests in JSC Chamber-A

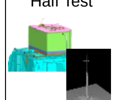
Pupil Alignment Test



Rogue Path Test

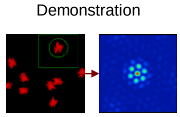


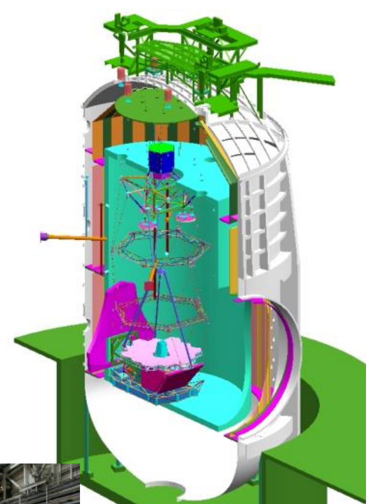
Pass-and-a-Half Test



Primary Mirror WFE Test

End-to-End WFSC Demonstration



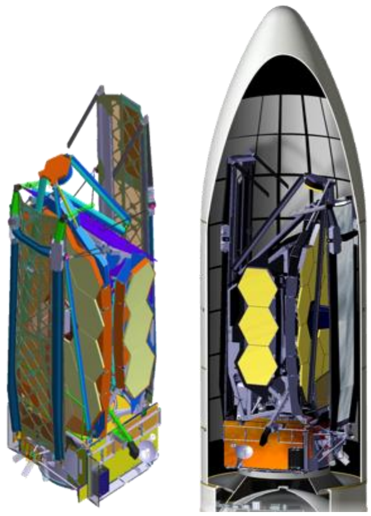


Chamber A:

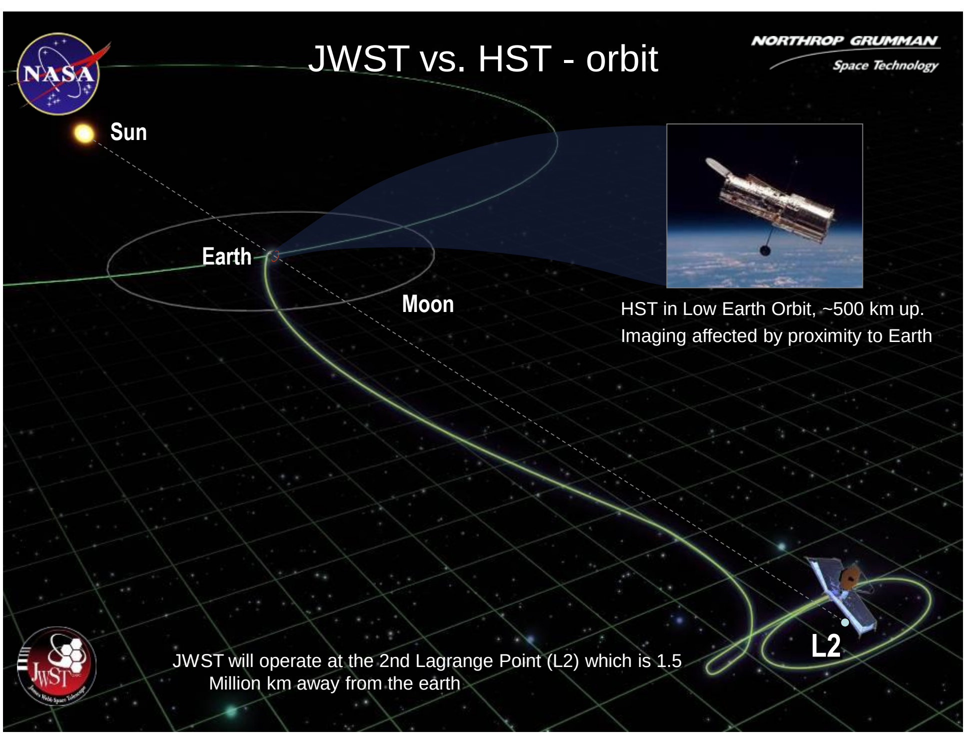
- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

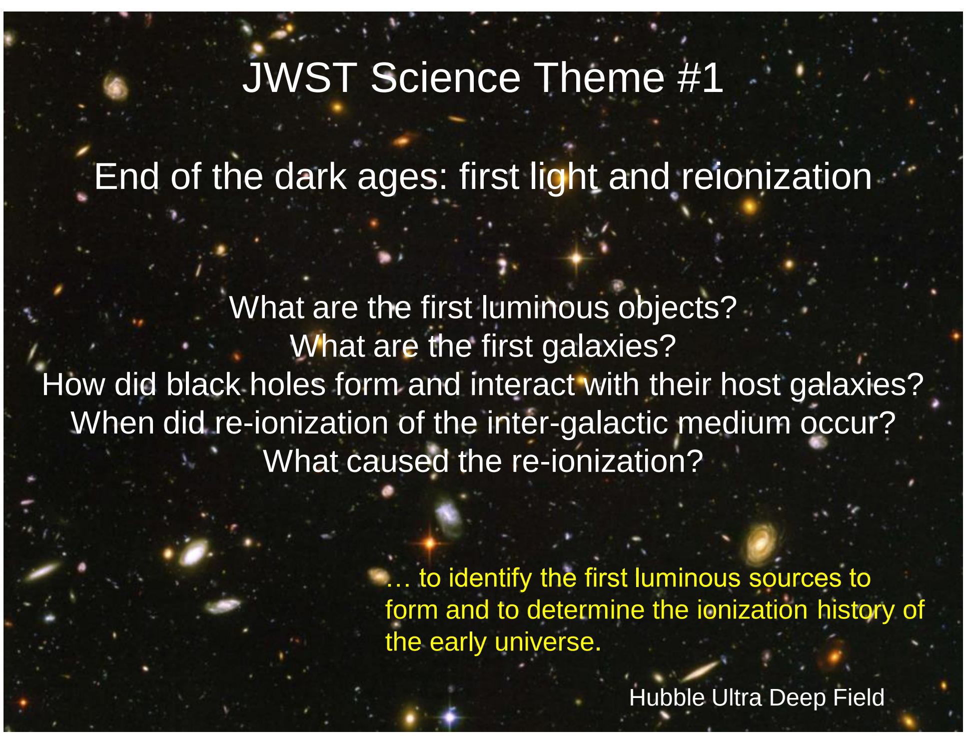
JWST Launched on Ariane 5 Heavy

JWST folded and stowed for launch in 5 m dia x 17 m tall fairing



Launch from Kourou Launch Center (French Guiana) to L2




JWST Science Theme #1
End of the dark ages: first light and reionization
What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did re-ionization of the inter-galactic medium occur?
What caused the re-ionization?
… to identify the first luminous sources to form and to determine the ionization history of the early universe.
Hubble Ultra Deep Field

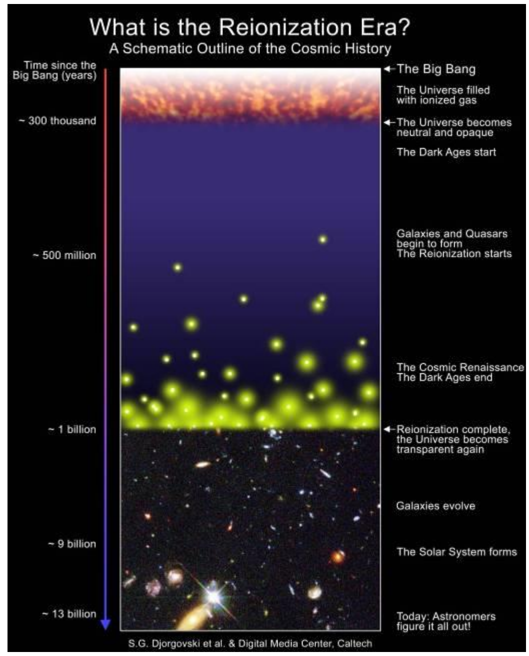
When and how did reionization occur?

Re-ionization happened at z > 6 or < 1 B yrs after Big Bang.
- WMAP says maybe twice?

Probably galaxies, maybe quasar contribution

Key Enabling Design Requirments:
- Deep near-infrared imaging survey (1nJy)
- Near-IR multi-object spectroscopy
- Mid-IR photometry and spectroscopy

JWST Observations:
- Spectra of the most distant quasars
- Spectra of faint galaxies



JWST Science Theme #2:

The assembly of galaxies

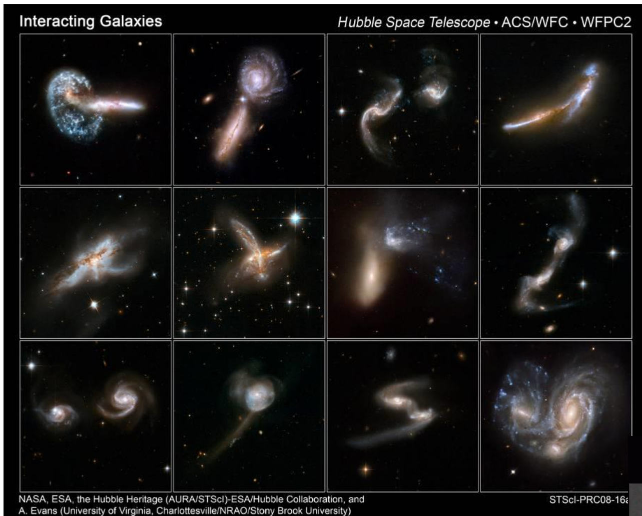
How did the heavy elements form?
How is the chemical evolution of the universe related to galaxy evolution?
What powers emission from galaxy nuclei?

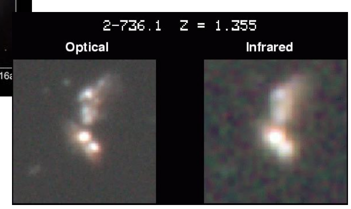
When did the Hubble Sequence form?
What role did galaxy collisions play in their evolution?
Can we test hierarchical formation and global scaling relations?
What is relation between Evolution of Galaxies & Growth/Development of Black Holes in their nuclei?

… to determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.

M81 by Spitzer

Distant Galaxies are "Train Wrecks"





Merging Galaxies = Merging Black Holes

Combined Chandra & Hubble data shows two black holes (one 30M & one 1M solar mass) orbiting each other – separated by 490 light-years. At 160 million light-years, these are the closest super massive black holes to Earth.

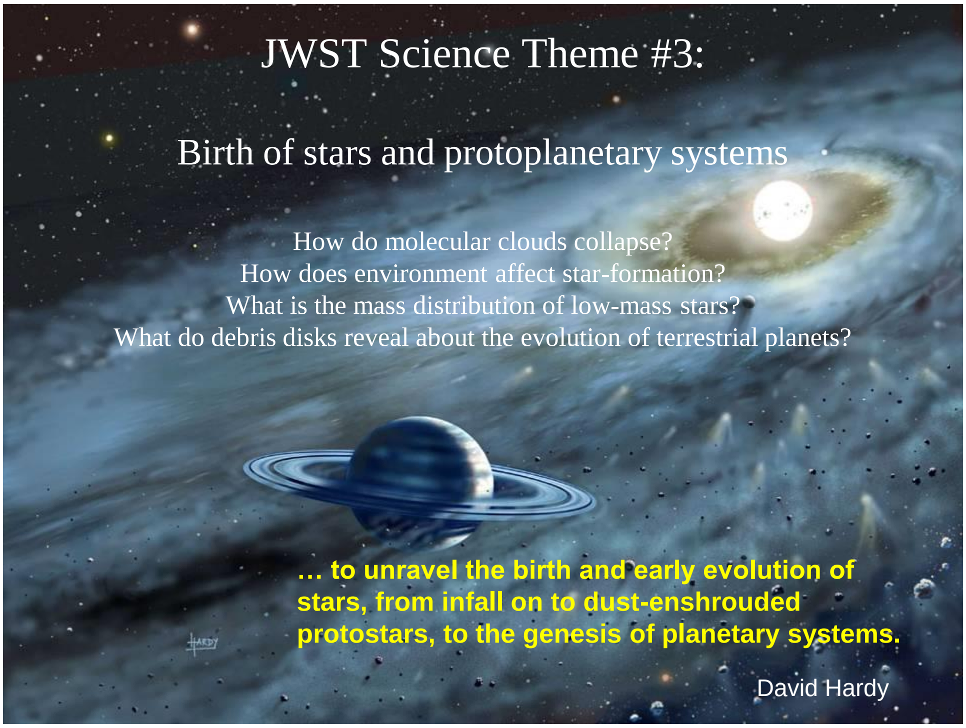
Theory says when galaxies collide there should be major disruption and new star formation.

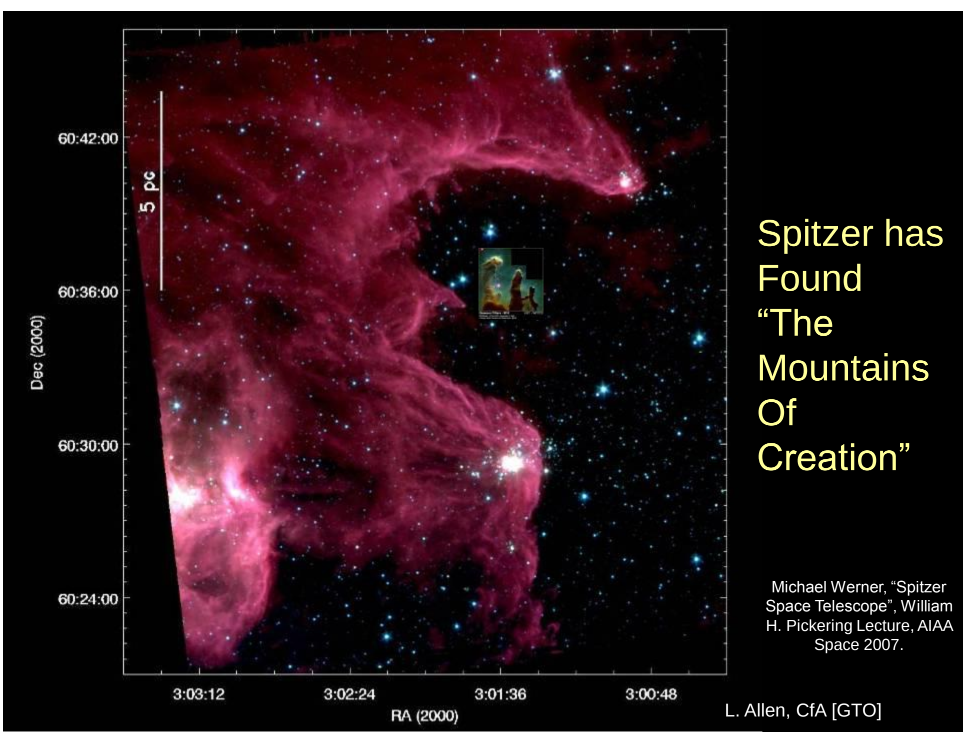
This galaxy has regular spiral shape and the core is mostly old stars.

These two galaxies merged with minor perturbations.

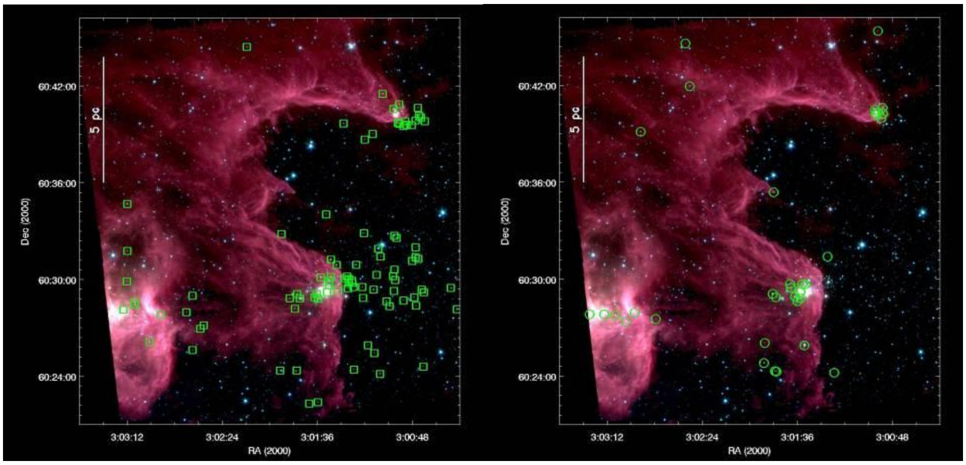
Galaxy NGC3393 includes two active black holes
X-ray: NASA/CXC/SAO/G.Fabbiano et al; Optical: NASA/STScI

Charles Q. Choi, SPACE.com, 31 August 2011


JWST Science Theme #3:
Birth of stars and protoplanetary systems
How do molecular clouds collapse?
How does environment affect star-formation?
What is the mass distribution of low-mass stars?
What do debris disks reveal about the evolution of terrestrial planets?
… to unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.
David Hardy


60:42:00
60:36:00
60:30:00
60:24:00
Dec (2000)
5 pc
3:03:12
3:02:24
3:01:36
3:00:48
RA (2000)
Spitzer has Found "The Mountains Of Creation"
Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.
L. Allen, CfA [GTO]

The Mountains Tell Their Tale
Interstellar erosion & star formation propagate through the cloud



Young (Solar Mass) Stars are Shown in This Panel

Really Young Stars are Shown in This Panel

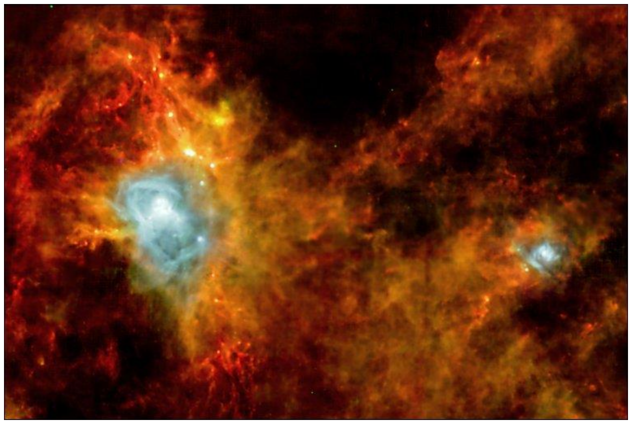
Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

Stellar Shockwave

Shockwave created by Zeta Ophiuchi which is moving towards the left at about 24 kilometres per second.

STARSTUFF IMAGE by Stuart Gary, ABC Science, 20 July 2015

Star Formation in Dust/Gas Cloud



Herschel discovered 700 newly-forming stars condensing along filaments of dust in a never before penetrated dark cloud at the heart of Eagle Nebula.

Two areas glowing brightest in icy blue light are regions where large newborn stars are causing hydrogen gas to shine.

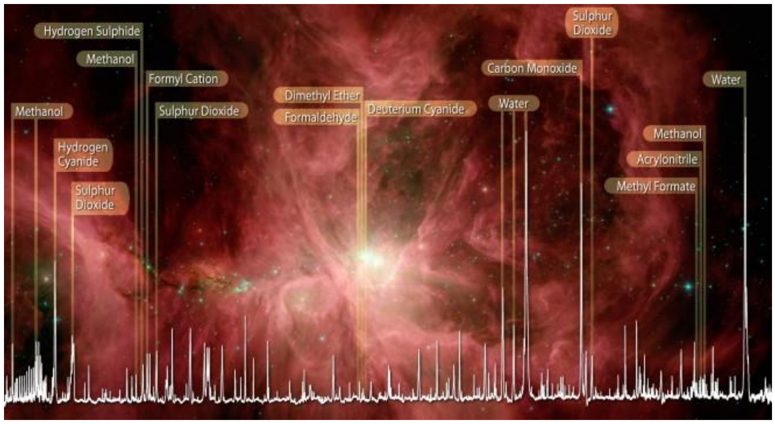
SPACE.com 16 December 2009

Orion Nebula Protoplanetary Discs

Hubble has discovered 42 protoplanetary discs in the Orion Nebula

Credit: NASA/ESA and L. Ricci (ESO)

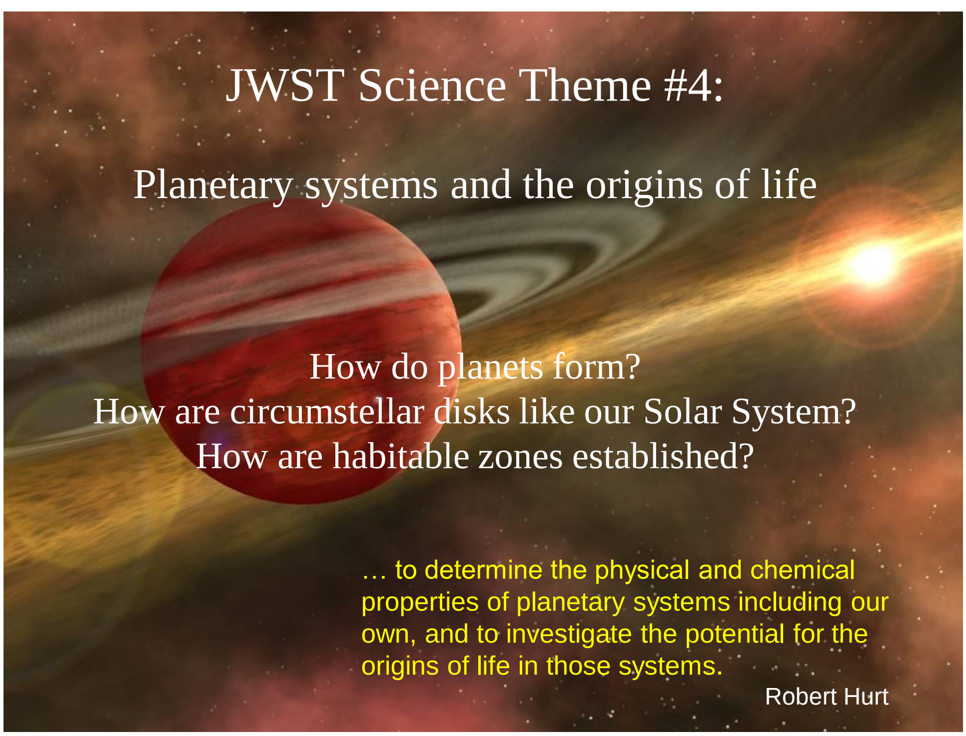
All of Life’s Ingredients Found in Orion Nebula



Herschel Telescope has measured spectra for all the ingredients for life as we know them in the Orion Nebula.

(Methanol is a particularly important molecule)

Wired.com Mar 2010



Planetary Formation Questions and 2 Models

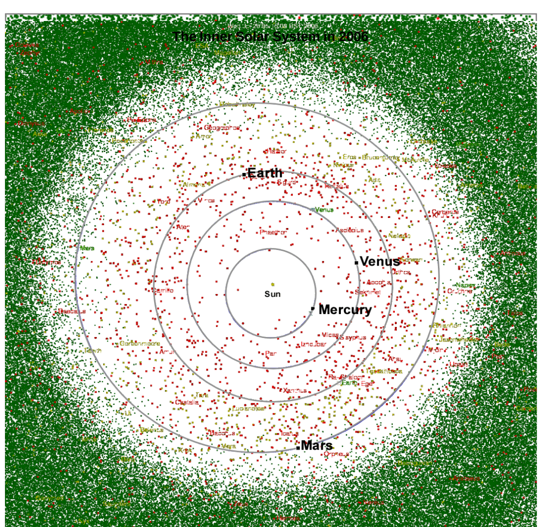
- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestrial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems) and remnant disks?
- What is the source of water and organics for planets in habitable zones?
- How are systems cleared of small bodies?
- What are the planetary evolutionary pathways by which habitability is established or lost?
- Does our solar system harbor evidence for steps on these pathways?

History of Known (current) NEO Population

2006

Earth Crossing

Outside Earth's Orbit

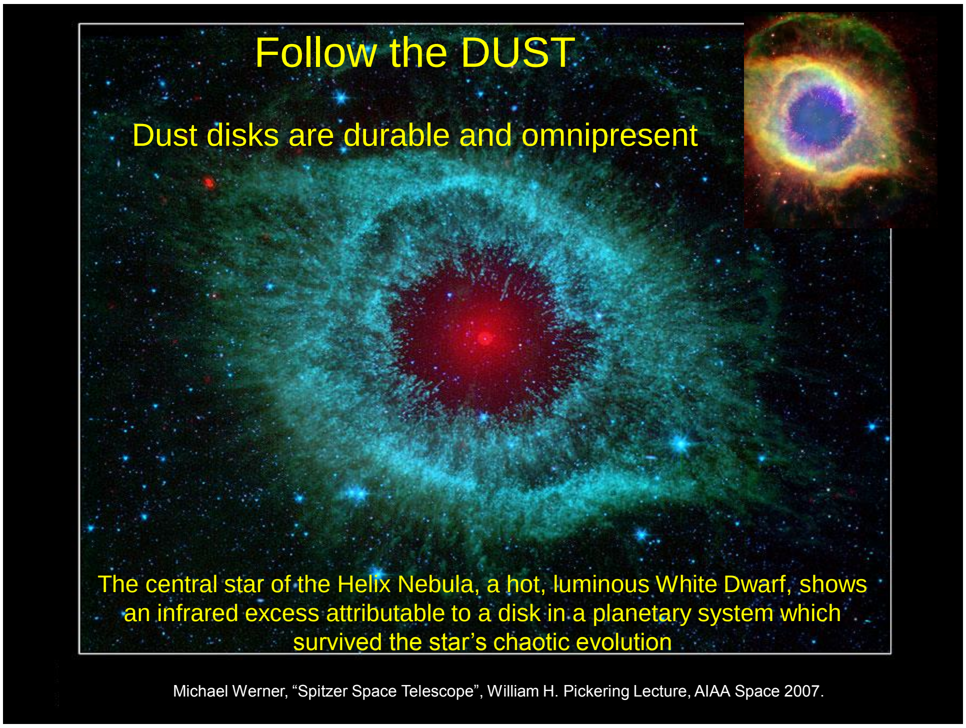


Known
- **340,000 minor planets**
- **~4500 NEOs**
- **~850 Potentially Hazardous Objects (PHOs)**

Scott Manley

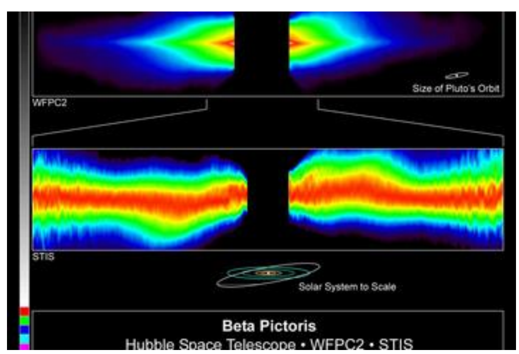
Armagh Observatory

Landis, "Piloted Flight to a Near-Earth Object", AIAA Conference 19 Sep 07



Planetary System Formation effects Dust

'Kinks' in the debris disk around Beta Pictoris was caused by the formation and subsequent migration of a Jupiter-sized planet called Beta Pictoris b.

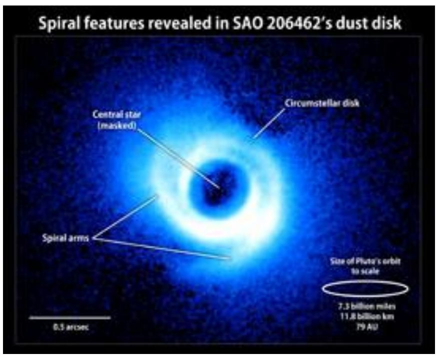


The planet orbiting Beta Pictoris has caused a kink in the debris disk surrounding the star, as seen in this false-color image from the Hubble Space Telescope. CREDIT: Sally Heap (GSFC/NASA)/ Al Schultz (CSC/STScI, and NASA)

Nola Taylor Redd, SPACE.com; 08 December 2011

Spiral Arms Hint At The Presence Of Planets

Disk of gas and dust around a sun-like star has spiral-arm-like structures. These features may provide clues to the presence of embedded but as-yet-unseen planets.



Near Infrared image from Subaru Telescope shows disk surrounding SAO 206462, a star located about 456 light-years away in the constellation Lupus. Astronomers estimate that the system is only about 9 million years old. The gas-rich disk spans some 14 billion miles, which is more than twice the size of Pluto's orbit in our own solar system.

Photonics Online 20 Oct 2011

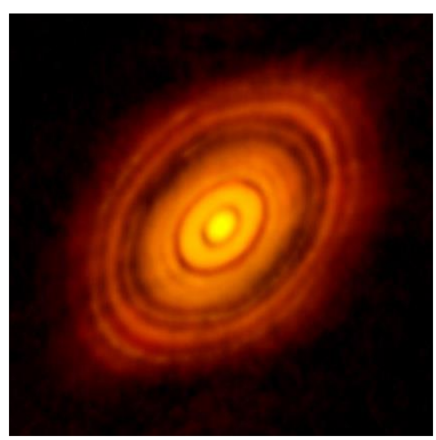
Direct Imaging of Planet Formation

ALMA is mm/sub-mm 15-km baseline array telescope producing a 35 mas resolution image. (10 m telescope at 500 nm has 10 mas)

HL Tau is 1 million year old 'sun-like' start 450 light-years from Earth in constellation Taurus.

Concentric rings separated by gaps suggest planet formation.

HL Tau is hidden in visible light behind a massive envelope of dust and gas. ALMA wavelength sees through dust.



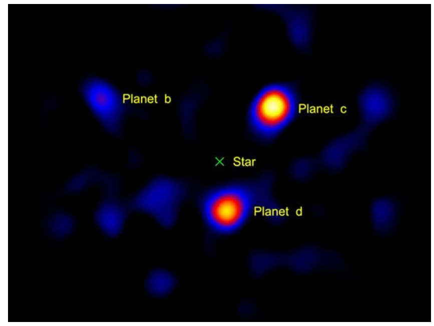
ALMA image of the young star HL Tau and its protoplanetarydisk. This best image ever of planet formation reveals multiple rings and gaps that herald the presence of emerging planets as they sweep their orbits clear of dust and gas. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

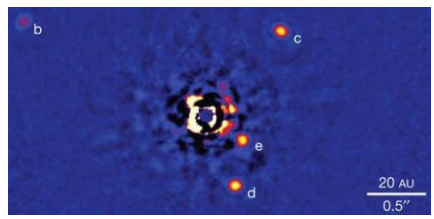
HR 8799 Planet (b)

HR 8799 Planet (b) has water, methane and carbon monoxide in its atmosphere.

HR 8799 is 129 light-years from earth and 1.5X the size of our sun in the constellation Pegasus.

Planet (b) is 7X mass of Jupiter

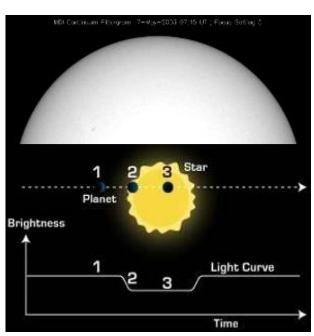


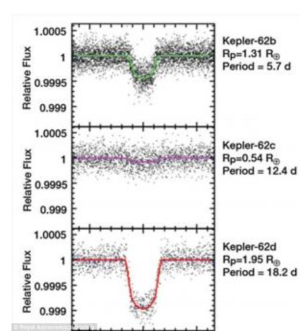


RT.com March 13, 2015

Transit Method Finds Planets

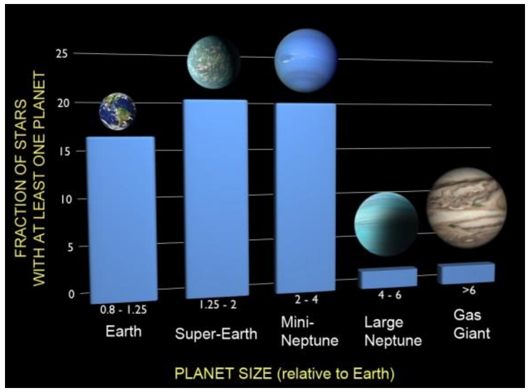
Kepler (launched in 2009) searched for planets by staring at 165,000 stars looking for dips in their light caused when a planet crosses in front of the star.





Kepler has found over 1000 ‘confirmed’ planets and over 4000 potential planets.

Nearly All Stars have Planets



Our galaxy has 100B stars of which 17B are like ours, so our galaxy could have 17B Earth size planets.

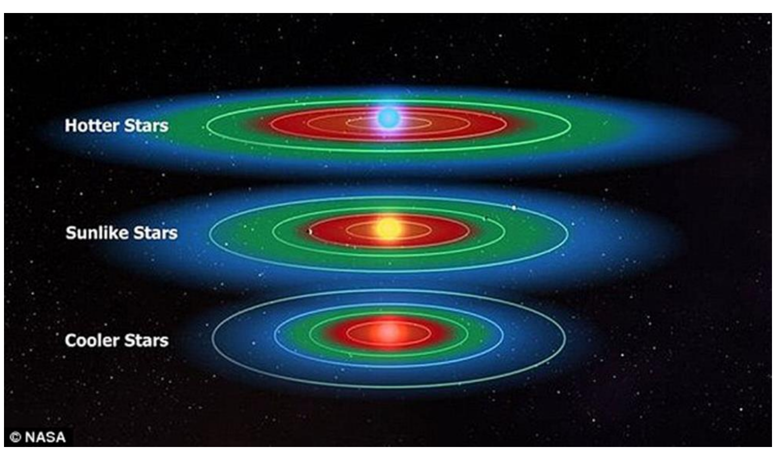
But only a few will be in Habitable Zone

Also, need a moon.

Nancy Atkinson; Universe Today; January 7, 2013

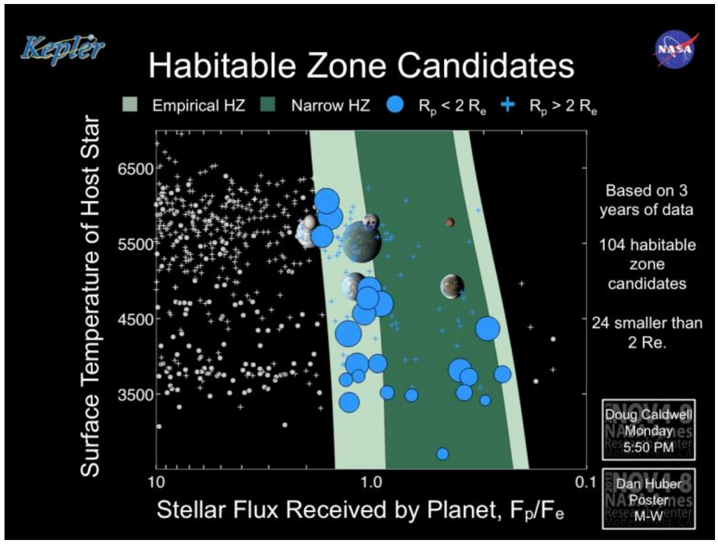
Habitable Zone

Life requires water. Liquid water can only exist in the 'Goldilocks'' Zone. The hotter the star, the further away the zone.



'Billions of stars' in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com, 18 March 2015

> 100 Habitable Zone Planet Candidates
> 24 smaller than 2 Earth Radii



Batalha, Kepler Conference Nov 2013

All Stars may have 1 to 3 HZ Planets

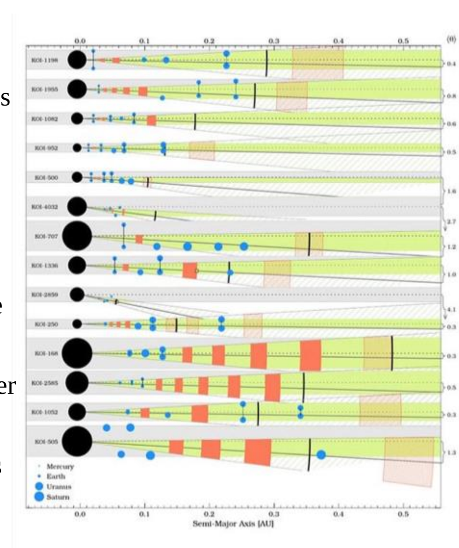
Titius-Bode law (used to predict Uranus) states that ratio between the orbital period of the first and second planet is the same as the ratio between the second and the third planet and so on.

Thus, if you know how long it takes for some planets to orbit a star, you can calculate how long it takes for others to orbit and can calculate their position in the planetary system.

Blue dots show planets measured by Kepler in 151 systems.

Red boxes predicted ‘missing’ 228 planets

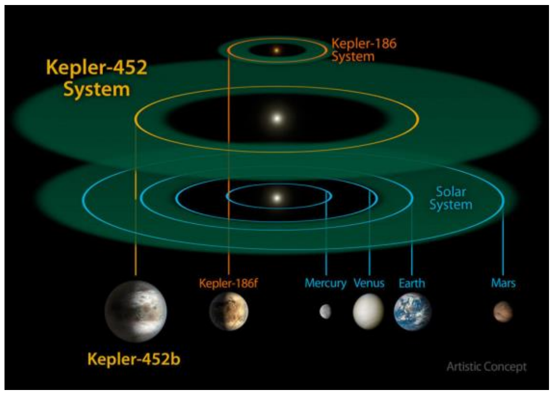
Average of 1 to 3 HZ planets per star.



'Billions of stars' in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com, 18 March 2015

Kepler 452b

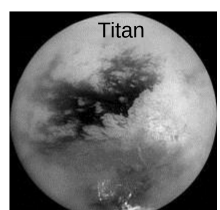
23 July 2015 NASA announced the confirmed discover of an Earth ‘cousin’ orbiting a star in the ‘habitable zone’. Planet is 60% larger than Earth with a 385 day orbit. Its Star is 1400 light years from Earth in the constellation Cygnus. Estimated age of the planet is 6B years compared to our own 4B years.



The size and scale of Kepler-452 system is compared to the solar system. Kepler-186 is a miniature solar system that would fit entirely inside the orbit of Mercury.

(Credit:NASA/JPL-CalTech/R. Hurt)

How are habitable zones established?



Source of Earth’s H_20 and organics is not known

Comets? Asteroids?

History of clearing the disk of gas and small bodies

Role of giant planets?

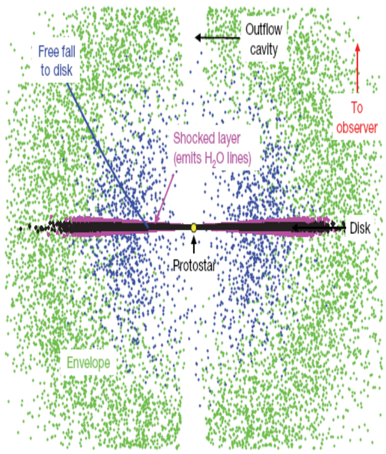
JWST Observations:

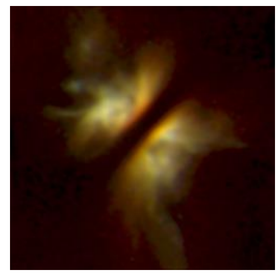
Comets, Kuiper Belt Objects

Icy moons in outer solar system

Where does the water come from?

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk

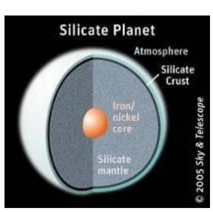


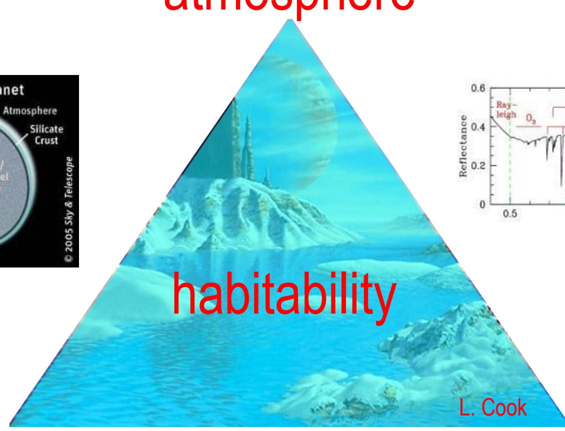


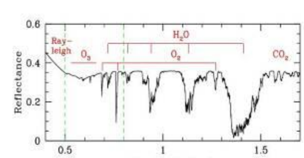
Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

Search for Habitable Planets

atmosphere







interior

surface

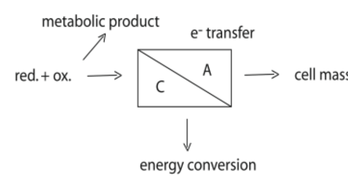
Sara Seager (2006)

Search for Life

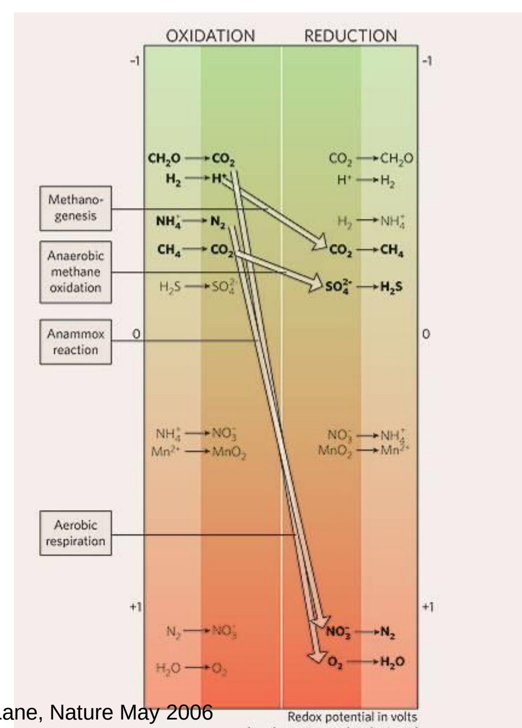
~~What is life?~~

What does life do?

Life Metabolizes



Sara Seager (2006)



Lane, Nature May 2006

All Earth life uses chemical energy generated from redox reactions

Life takes advantage of these spontaneous reactions that are kinetically inhibited

Diversity of metabolisms rivals diversity of exoplanets

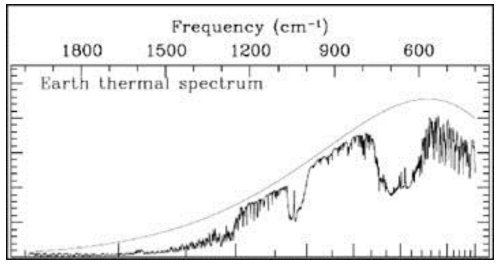
Sara Seager (2006)

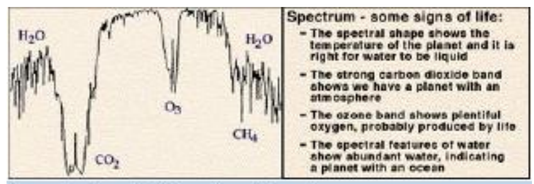
Bio Markers

Spectroscopic Indicators of Life

Absorption Lines

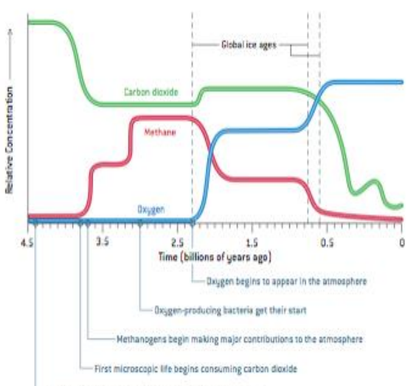
- $CO2$
- Ozone
- Water
- “Red” Edge



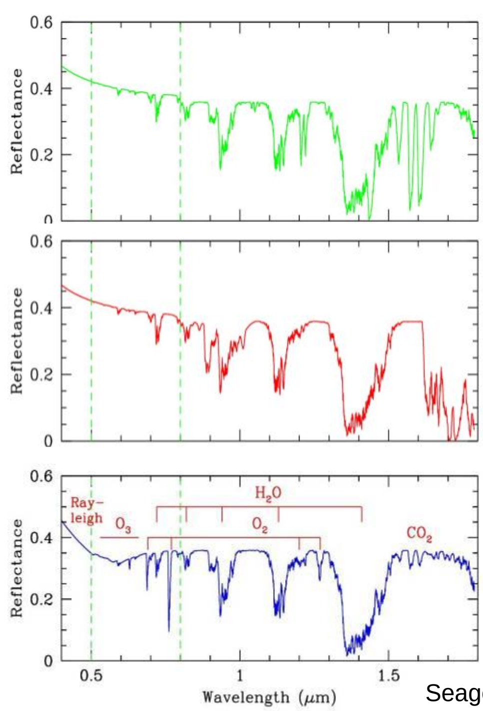


Example signs of life from chemical spectra.
Credit: NASA JPL

Earth Through Time



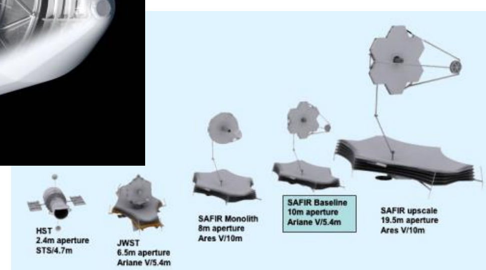
Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon



Seager

Beyond JWST

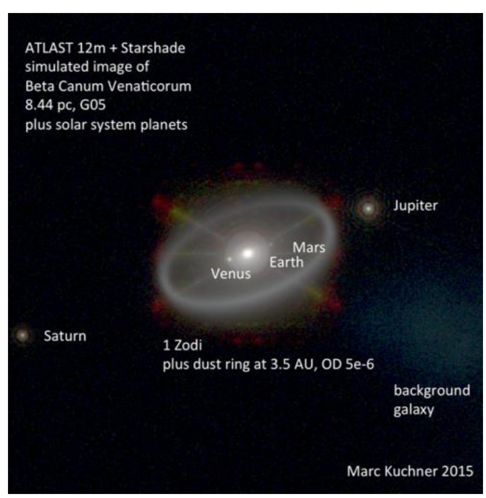
Heavy Lift Launch Vehicle enables even larger telescopes
- 8-m UV/Optical Telescope or
- 24-m Far-IR Telescope



Direct Imaging

Giant Space Telescopes will be able to directly image Planetary Systems using either internal coronagraphs or external star shades.

Simulated image for a 12-m telescope, a 100-m star shade, and 1 day exposure.

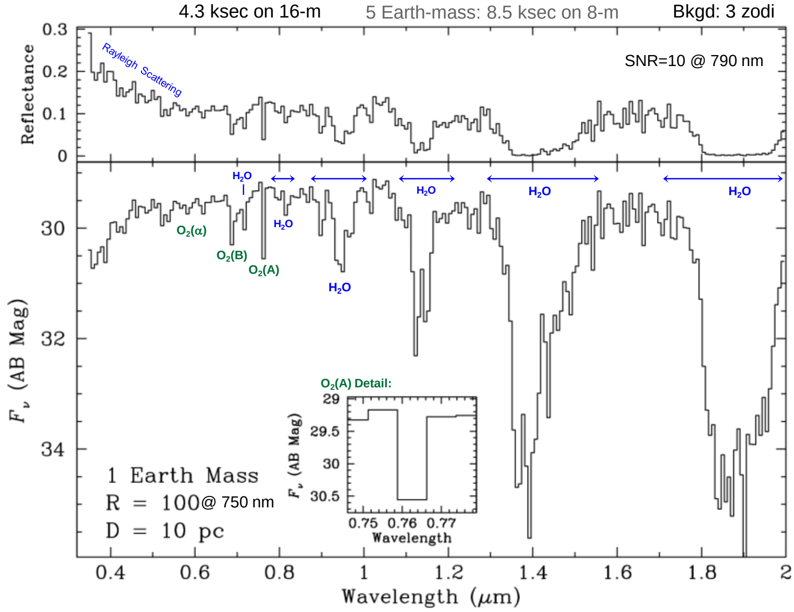


R=100 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc

Exposure: 51 ksec on 8-m
4.3 ksec on 16-m

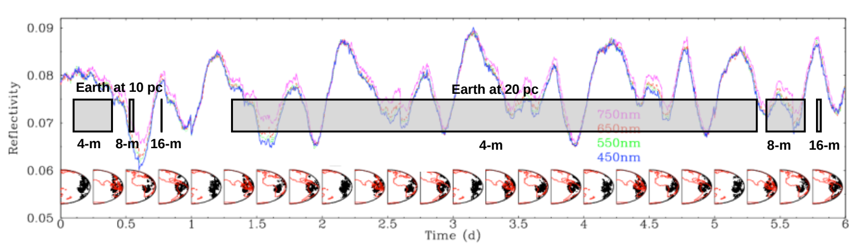
Reflectance ∝ (Planet Mass)$^{2/3}$
5 Earth-mass: 8.5 ksec on 8-m

Bkgd: 3 zodi



Marc Postman, "ATLAST", Barcelona, 2009

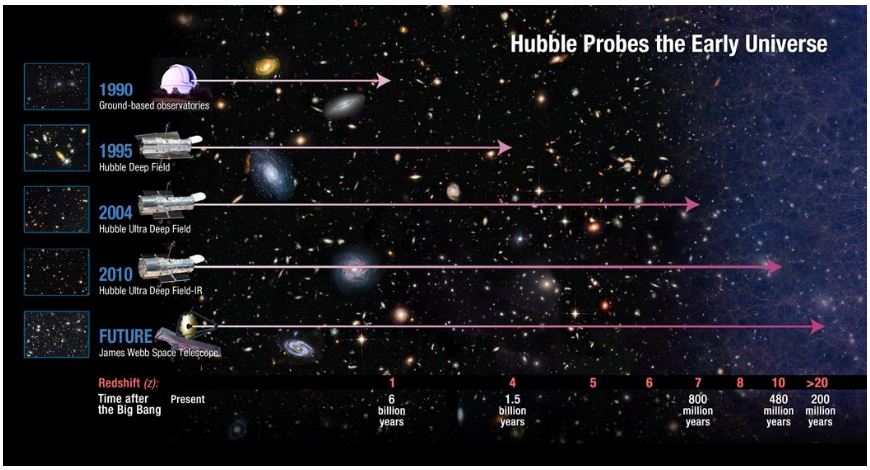
Detecting Photometric Variability in Exoplanets



Marc Postman, "ATLAST", Barcelona, 2009

JWST – the First Light Machine

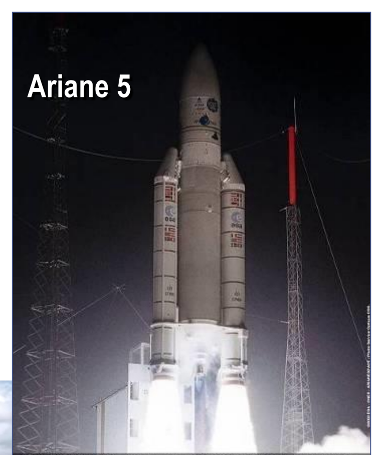
With its 6X larger collecting aperture, JWST will see back in time further than Hubble and explore the Universe's first light.



Countdown to Launch

JWST is

- making excellent technical progress
- will be ready for launch late 2018
- will be the dominant astronomical facility for a decade undertaking a broad range of scientific investigations



1000s of Scientists and Engineers in USA and around the world are working to make JWST.